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SPACE ROBOTICS

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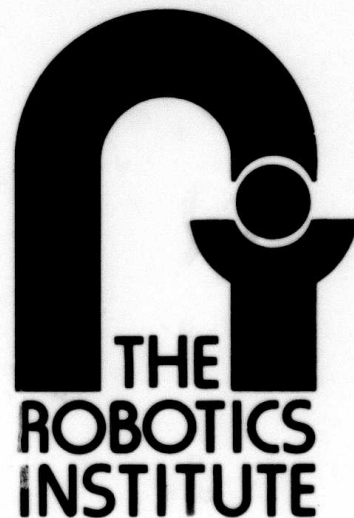
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Space Robotics

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Abstract

This report surveys the possible applications and technical feasibility of robots in space. The future of the space program in the time frame of 1980-2000 is first assessed, including space exploration, global information services, and space utilization. The critical technologies needed to support the projected space program are then considered, including the need for general purpose, remote intelligence and manipulation. Teleoperators are discussed as a possible means of meeting this requirement and are found not to be satisfactory due to communication time delays and bandwidth limitations, and human costs and performance limits. Autonomous space robots are proposed as a solution and several detailed scenarios for their use are presented. The technical feasibility of space robotics is evaluated by examining the requirements, state of the art, and research needed for each of the subsystems of a space robot. These include manipulators, sensors, navigation, guidance, propulsion, surface locomotion, computing and control, communications, electrical power, and spacecraft structure. Finally, a research program is outlined for the development of autonomous space robots.

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1. Executive Summary

This report surveys the possible applications and technical feasibility of robots in space. The future of the space program in the time frame of 1980-2000 is first assessed, including space exploration, global information services, and space utilization. The critical technologies needed to support the projected space program are then considered, including the need for general purpose, remote intelligence and manipulation. Teleoperators are discussed as a possible means of meeting this requirement and are found not to be satisfactory due to communication time delays and bandwidth limitations, and human costs and performance limits. Autonomous space robots are proposed as a solution and several detailed scenarios for their use are presented. The technical feasibility of space robotics is evaluated by examining the requirements, state of the art, and research needed for each of the subsystems of a space robot. These include manipulators, sensors, navigation, guidance, propulsion, surface locomotion, computing and control, communications, electrical power, and spacecraft structure. Finally, a research program is outlined for the development of autonomous space robots.

Future space applications can be classified as exploration, global information services, or utilization of space. Exploration consists of earth orbiting satellites such as space laboratories and large antennas, solar and planetary orbiters, and surface probes of the moon and Mars. Global information services include observation of and data collection from the land, sea, and atmosphere, global communications, and global navigation. Space utilization encompasses energy sources, materials and manufacturing, and human services in space.

The critical space technology needs are data management, very low cost space transportation, and assembly of large structures in space. The most important factor in determining the future of space is the cost of transporting material from the earth into orbit. While the space shuttle can deliver a kilogram into low earth orbit for $500, this figure must be decreased by an order of magnitude to make many applications economical. The tremendous volume of data being received from space, currently 10^{12} bits per day, necessitates data management systems to handle acquisition, reduction, analysis, and distribution. The deployment, fabrication, assembly, and repair of very large space structures is required for applications such as large antennas, a solar power satellite, materials processing and manufacturing, or a permanent space station.

Space construction, satellite deployment, retrieval, and servicing, and space rescue missions all require intelligent action and manipulation in space. Due to the high cost of maintaining humans in space, one proposal to satisfy this need is teleoperation: the use of manipulator systems remotely controlled by human operators in response to remote sensory input. Teleoperator types include rigidly attached, tethered, surface, and free-flying systems. Teleoperator technology encompasses manipulators, sensors, and man-machine communication. However, the disadvantages of teleoperators include transmission time delays, limits on information flow, personnel costs on the ground, and operator performance limits.

For these reasons, autonomous space robots are proposed as an alternative to teleoperators. Application scenarios include deep space probes, lunar or Mars rovers, earth orbiting robots for satellite maintenance or repair and space construction, and space rescue robots.

The feasibility of such robots depends on the state of technology for each of the necessary subsystems. Manipulators are required to carry out the tasks of the robot. Sensors are necessary for effective manipulation

and data collection. Navigation, guidance, and propulsion are needed to get the robot to its target destination. Surface mobility, locomotion, and path planning are essential to a lunar or Mars rover. A computing and control system is critical to the operation of all other systems and also needed for machine intelligence and on-board data management. A communications system is required for the transmission of commands and data between earth and the robot and also for communication between robots. An electrical power system is necessary to run the other systems. Finally, the robot must be housed in a spacecraft in order to protect it from the harsh environment and hazards of space flight.

The goal of an autonomous space robot can best be achieved by a research program consisting of a series of incremental goals embodied as space missions. Such a program is presented as a four stage effort. The first stage is an intelligent sensing robot, designed to close the technology gap between earth-based and space qualified computer systems. The second step is a general purpose, free flying space robot addressing the issues of onboard navigation, guidance, propulsion, and control of manipulator systems. The next stage is the development of lunar or planetary roving vehicles for surface exploration. The final step is the realization of space construction robots, the major additional problem being the cooperation of multiple robots to accomplish a single task.

Anthropomorphism in robot design is the tendency to design robots that closely imitate their human counterparts. It is pointed out that anthropomorphism can severely limit the range of possible solutions to robotic problems, especially in an arena as hostile to humans as the space environment.

The economics of space dictate that the future of space will ultimately depend on whether space operations become profitable. However, the government must take the lead in developing space technologies. The rate at which space technology advances is more often determined by political considerations rather than scientific ones.

2. Introduction: The Future of Space

An assessment of the role of robotics in space must begin with an appraisal of the future applications of space. This section presents a picture of the future of space up to the year 2000. Much of it is based on the report of the "Outlook for Space" study group which was commissioned by NASA to propose and forecast future directions for the space program in the time frame of 1975-2000 [61]. The future applications envisioned by the study group fall into three broad areas: space exploration, global information services, and space utilization or industrialization. It should be noted that many of the applications described below constitute only very preliminary proposals that have not even undergone feasibility studies. The mission descriptions are primarily from [31]. Many of these applications require smart sensors, spacecraft mobility, flexible manipulators, and machine intelligence in order to be successful.

2.1 Space Exploration

Space exploration missions can be classified as earth orbiting, solar and planetary orbital missions, and surface probes.

A spacelab instrument program would put a large package of scientific instruments into earth orbit. Long term observations of the sun from earth orbit and solar mapping could be accomplished by an earth orbital solar observatory. An astrophysics space lab would look toward outer space for surveys of objects and phenomena. A research program aimed at modelling the atmosphere could be carried out by an atmospheric physics laboratory.

The performance of many large antennas and telescopes is limited by their physical size and geometric precision. The zero gravity environment of earth orbit allows very large structures, with dimensions measured in kilometers. In addition, earth orbit is far removed from the optical and radio haze which pervades the atmosphere. An X-ray observatory orbiting the earth could use the high bandwidth of X-rays to study other stars and galaxies. Intergalactic phenomena could also be investigated by space-based radio telescopes with reflectors up to three kilometers in diameter. Bekey and Naugle [9] have proposed space-based devices for detecting gravity waves, astrometers for improving angular resolution of astronomical measurements, and very long base interferometry, using a baseline between orbiting and ground antennas, to accurately measure distances of astronomical objects.

A second category of space exploration missions utilizes solar and planetary orbiters. The Galileo-Jupiter orbiter, scheduled to fly in 1985, will release a probe into the Jovian atmosphere and will repeatedly engage in close flybys with Jupiter's moons. A Saturn orbiter dual probe would release a probe into Saturn's atmosphere and also a hard landing probe onto Titan, one of Saturn's moons. The surface of Venus could be mapped with synthetic aperture orbital imaging radar. A solar polar mission calls for a spacecraft to orbit the Sun out of the ecliptic plane.

A third class of space exploration missions is comprised of surface probes, in particular probes of Mars and the moon. A proposed Mars sample return mission would include vehicles for descending to the surface and returning to the orbiters, devices to penetrate the surface, airplanes that would fly in the atmosphere, and roving surface vehicles. The surface of the moon could be surveyed and prospected for resources using lunar rovers.

Due to speed of light communication delays, exploration missions to other planets must incorporate a significant degree of autonomy and be capable of responding to high-level commands from earth. This requires advanced robotics and machine intelligence technology.

2.2 Global Information Services

The second broad area of space applications is earth-related information services. This area can be broken down into observation and data collection, communication, and global navigation.

2.2.1 Observation and Data Collection

Observation and data collection refers to using earth orbiting satellites to gather, process, and transmit data about the land, sea, or atmosphere. Soil moisture conditions can be detected by satellite and used for world-wide crop prediction and irrigation planning. Global crop forecasting could be accomplished by a system of high-bandwidth satellites. Disasters such as forest fires, insect infestations, and tornadoes could be detected and partially predicted by a system of disaster warning satellites. A system of geological mapping satellites could regularly update geological maps used for ground resource exploration.

In the area of observation and data collection of the oceans, a follow-on to the Seasat satellite will study the sea surface with high precision from a low polar orbit. A Tiros-O satellite could measure sea and air temperatures, wind velocities, and polar sea/ice movements. Twelve- to eighteen-hour forecasts of sea conditions and sea resources could be provided by a system of high resolution sea survey satellites.

Atmospheric observation by satellite includes Stormsat which would carry atmospheric sounders and imaging radiometers in geosynchronous orbit in order to predict and monitor heavy storms. Global measurements of temperature, humidity, winds, clouds, etc. could be provided by a large scale system of weather survey satellites.

2.2.2 Global Communications

The second major area of global information services is global communications. Most currently orbiting satellites are communications satellites and communications will remain the predominant use of space in the near future. Microwaves in the 1-10 gigahertz range provide the high bandwidth necessary for large scale communications. Bekey and Mayer [8] propose several applications and rate their development risk as low, medium, or high.

One promising low risk concept is a person-to-person wrist radiotelephone communications system. Such a system would require a single satellite in geosynchronous orbit, would use wrist transceivers costing as little as $10, could be available in ten years, and would cost on the order of $300 million (in 1976 dollars) to develop. This is an example of what Von Puttkamer [63] calls "complexity inversion": putting the complexity of a system into space so that the corresponding ground elements are small, simple, inexpensive, and therefore can proliferate. This is exactly opposite to the approach that has been taken up to now.

An electronic mail system described by Bekey and Meyer [8] involves TV camera scanning of documents at

the sending post office, transmission of the signal via satellite, and facsimile reproduction of the document at the receiving post office. Such a scheme could interconnect 100,000 post offices in 50% of the contiguous United States with a total capacity of 100 billion pages per day, using a single geosynchronous satellite. The development risk would be low at a cost of $430 million. An obvious extension of such a scheme is direct electronic mail interconnecting business and home computers.

An example of a medium development risk idea is 3-dimensional holographic teleconferencing. From a conference room fitted with a multicolor laser illuminator, a "camera" picks up a holographic image and relays it via satellite to a set of laser projectors in a second conference room across the country. The result is that completely lifelike, 3-dimensional color images of the participants can speak, move around, present solid models, and do everything except shake hands. Such a vision could radically alter travel patterns and geographical population distributions, since many people would no longer be required to live near their work.

2.2.3 Global Navigation

The final major division of space information services is global navigation. For example, by putting radar reflectors into orbit, radar systems can be built that are not limited by the earth's horizon. Such a scheme could support a single multi-national air traffic control system with a low risk of development for about $330 million. The satellites would consist of lightweight passive metallized-mesh sheets stretched in frames.

Bekey and Naugle [9] describe a satellite system for direct air, sea, and land navigation that incorporates collision and hazard warnings.

One medium development risk possibility is a personal navigation system employing a satellite and inexpensive wrist devices similar to those of the personal communications system. The satellite would keep track of the location of each of the devices, within a hundred yards, and the user would key in the coordinates of his destination (home, office, place to be visited, etc.) and instantly read out the distance and direction to his goal. The personal communication and navigation systems could be combined into a single wrist transceiver.

Most of these information systems require heavy, high powered satellites with large antennas in geosynchronous (35,900 kilometer) orbits. They will require intelligent sensing and data processing capabilities. In addition, their cost and size will make in-orbit servicing and repair cost-effective. This requires robots with flexible manipulators and diagnostic capabilities.

2.3 Utilization of Space

The third major area of future space applications is direct utilization or industrialization of space itself. Space utilization can be subdivided into three main categories: energy production and distribution, space manufacturing, and human services.

2.3.1 Energy

The solar power satellite is a very prominent and much studied concept for obtaining energy from space [43]. The basic idea is a very large (approx. 100 sq. km.) satellite in geosynchronous orbit that converts solar energy to electricity through solar cells or thermal techniques, and beams the power via microwaves to a receiving antenna on earth. Continuous daylight and the lack of intervening atmosphere and weather make a space solar power station an order of magnitude more effective than a comparable size earth facility. A four year concept evaluation program was recently completed by NASA and the Department of Energy. The major problems identified were: efficient energy conversion, efficient power transmission, transportation of large quantities of materials from the ground to low earth orbit and then to geosynchronous orbit, and fabrication and assembly of the huge structure in space. Development cost is projected at $50 to $100 billion over a 15-20 year period.

Another energy related concept is nuclear waste disposal in deep space [31]. This would involve launching hazardous material into low earth orbit and then boosting it into a trajectory that would take it out of the solar system.

A particularly imaginative idea presented by Bekey and Meyer [9] is night illumination of cities by orbiting solar reflectors. About ten, 1000 ft. diameter thin film mirrors could illuminate a 180 mile diameter area to the level of ten times the brightness of a full moon.

2.3.2 Space Manufacturing

Many manufacturing processes can be improved in the environment of earth orbit. The relevant features of the space environment are the absence of gravity and the absolute vacuum. The implications for manufacturing are that objects require no supports, and there is no convection in gases or liquids due to density differences or thermal gradients. For example, gases remain dissolved in liquids. These factors allow extreme purification of a melt, formation of deposits or crystals from the vapor phase without contamination, and virtually faultless crystal growth.

Applications include the production of homogeneously doped semi-conductors and other homogenized electronic materials. In most processes, purification improves strength, corrosion resistance, catalytic activity, and magnetic and electrical properties, such as superconductivity. Containerless processing and positioning, by bounding materials with electromagnetic or acoustic fields, can produce surfaces that are extremely smooth, such as those required in high precision optical instruments [11]. In addition, the zero gravity environment enhances electrophoretic separation of biological substances such as blood products [32].

2.3.3 Human Services in Space

The final category under space utilization is concerned with using space to provide human services and support. For example, a space health care system could develop and provide on-board health care to the passengers and crew of future manned missions [31]. It is also likely that the weightless environment of space could be helpful in the treatment of many diseases, particularly muscular and skeletal disorders.

A permanent manned space station is a key stepping stone on the way to many future space applications. A

space station would probably be constructed modularly, each module being the size of one shuttle cargo load. Modules would be included for commercial processing, data processing, liquid storage and transfer, and maintenance, repair, checkout, and general storage [31].

The ultimate in human services is space colonization. A 1977 summer study group at NASA Ames Research Center [60] looked at the problems of space resources and space settlements. The fundamental research problem in this area is the design of a completely closed, fully regenerative life support system. The group also investigated habitat design.

The common feature of these space utilization proposals is that they all involve large structures in space. These structures would have to be assembled in space from smaller components that could be transported into earth orbit. This is a prime application for space robots.

3. Critical Technology Needs

There are three critical technology areas that NASA must develop in order to support the future space applications described in the previous section: very low cost space transportation, data management (which requires smart sensing and data processing), and the building of large structures in space (which requires mobile robots with manipulators).

3.1 Very Low Cost Space Transportation

The cost of many space applications is dominated by the expense of lifting heavy spaceships and materials out of earth's deep gravity well. Hence, the cost of space transportation is the single most important determining factor in the future of space. It is usually measured in dollars per kilogram of payload carried from the earth's surface to low earth orbit.

The current state of the art in space transportation is represented by the space shuttle. The shuttle blasts off vertically with the help of recoverable solid fuel booster rockets, injects itself into earth orbit, reenters the atmosphere behind a heat shield, and lands like a glider on a 4.5 kilometer runway. It can be reused up to an estimated 100 flights. The shuttle has a 300 cubic meter cargo hold and a 3 joint manipulator with a 15 meter range for payload deployment and retrieval. It can carry a payload of 30,000 kilograms into low earth orbit at a cost of about $500 per kilogram. Its first four orbital tests were quite successful.

Criswell [14] points out that the cost in fuel of boosting a kilogram into earth orbit, assuming a vehicle that is 100% efficient and 100% payload, is 30 cents. The difference between 30 cents and $500 is the technology gap in space transportation.

Improvements to the shuttle could reduce the cost to earth orbit to $200/kg. By the year 2000, a heavy lift chemical rocket such as the reusable Space Freighter could reduce this cost to $50/kg, and carry a payload of 425,000 kilograms.

Achieving costs for earth orbit below $50/kg will require significant innovation. Future high thrust engines may be electromagnetic, nuclear, or laser powered. Even more imaginative proposals include so-called skyhooks: structures or cables which extend from the earth's surface to an altitude in orbit and along which materials may be transported. These may be ballistically supported [55] or held in place by the centrifugal force of the earth's rotation [57].

Another aspect of space transportation concerns boosting payloads from low earth orbit to geosynchronous altitude. The difference between this problem and lifting material from the ground is that the effective lack of gravity allows low thrust engines to be operated over longer time periods to accomplish the orbital transfer. Proposals for powering a "space tug" operating between low earth and geosynchronous orbits include solar sailing, solar electric propulsion, and ion drives.

The high cost of lifting objects from the earth's surface motivates research toward obtaining materials for space systems from low gravity sources such as the moon, asteroids, or comets. Since the moon has a lower escape velocity than earth, only 1/22 as much energy is required to eject material from the moon as from

earth [14]. The absence of a lunar atmosphere means that a vehicle is not necessary for transportation from the moon. In addition, solar energy is abundant on the moon. The combination of these factors makes a long (about 1 km) solar powered, electromagnetic mass driver a practical means of launching materials from the lunar surface.

Lunar utilization [15] has been extensively studied and it has been found that the lunar regolith contains 90% of the elements required for space applications, the most notable deficiencies being hydrogen and oxygen [33]. A lunar precursor processor could use solar energy to extract materials from lunar soil delivered to the processor by rovers. The materials could be ejected from the moon by electromagnetic mass drivers or used on the moon to build a base of operations for a lunar survey and more advanced prospecting, mining, and processing operations.

More far-sighted proposals for obtaining raw materials to support space operations include towing asteroids and comets into earth orbit and mining them.

3.2 Data Management

The second critical technology area for the future of space is data management. Currently, 10^{12} bits per day of information are beamed at the earth from orbiting satellites and space probes elsewhere in the solar system [66]. This rate is equivalent to the transmission of all the information in the Library of Congress every two years. The data flow is expected to increase to between 10^{13} and 10^{15} bits per day by the year 2000 [48].

The problem with this data deluge is how to store it and provide access to required information both rapidly and at a reasonable cost. The state of the art in data management is represented by the LANDSAT system. A fully processed, reduced, annotated, and analyzed LANDSAT image with a resolution of 80 meters per picture element costs several thousand dollars and requires up to three months to deliver [31]. One estimate of what is feasible in this area is almost real time image processing and delivery, at a resolution of 2 centimeters per picture element, for about $10 per image [44].

This technology gap and how to close it is the subject of the NASA· End to End Data System (NEEDS) study. The current method of data collection is that satellites continually gather and transmit data throughout each orbit of their useful life cycle with the assumption that most data required by a user can be found somewhere in the huge volume of data stored. The idea behind NEEDS is that specific data will be requested by a user and then the appropriate satellite will be instructed to collect and transmit that particular data at the correct point in its orbit.

The technology needs for data management include better data acquisition, reduction, analysis, and distribution. Improved data acquisition requires higher resolution sensors and direct control of those sensors by observers at ground terminals. Data reduction technology requirements include advanced information coding techniques and intelligent sensors that only transmit useful data, such as a LANDSAT system that automatically stops transmitting data when the earth's surface is obscured by cloud cover. Note that satellite data is cataloged primarily by geographical location and time. Thus, it is very difficult to respond to queries of the form "show me a satellite photo of corn blight." Refined data analysis, information extraction, and classification systems are necessary to implement a content addressable space data bank. Finally, a computer network linking the principle sources and users of satellite data is required to accomplish near real time data distribution.

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3.3 Large Structures in Space

The third critical technology needed for the future of space is the ability to deploy, fabricate, assemble, and maintain large structures in space. This is an area in which robotics will play an extremely important role.

The space environment provides the opportunity to build and maintain very large structures with dimensions measured in kilometers. The reason is that the absence of forces such as gravity, wind, and earthquakes results in very low structural loads on the members of an orbiting structure.

The needs for such structures are many and varied. A permanent space station will be a large facility as will a materials and manufacturing plant. Space antennas with diameters up to a kilometer have been proposed. A practical solar power satellite would measure 5 km by 10 km [43].

Designs for such large structures include conventional beam and truss assemblies and several unconventional designs which take advantage of unique features of the space environment. Making use of the fact that most materials are stronger in tension than in compression, these designs stiffen and stabilize a structure by spinning it, orienting it along the gravity gradient, using the force of the solar wind, or running a current through the structure which interacts with the earth's magnetic field to produce the required mechanical forces.

The critical technology requirement in this area is how to construct and maintain large space structures. There are three possible ways of getting a structure larger than the shuttle cargo hold into space: deployment, assembly, or fabrication in space. Most future applications will require some combination of these three methods.

Deployment refers to placing a completely assembled structure that is folded or compressed in some fashion into the cargo area. Once the shuttle is in position, the structure has been removed by the manipulator, and the shuttle is clear of the structure, an automatic sequence is initiated which extends or unfolds each component of the structure. Examples include telescoping straight wire antennas, dish antennas which collapse like an umbrella, or solar panels which are fan folded. This is the method that has been used for conventional satellites and could also be used for large, thin film reflectors.

Once the collapsed size or weight of the structure exceeds one shuttle load, then it must be split into several loads and some assembly must be performed in space. Assembly involves removal of the components from the shuttle, alignment and orientation, docking of the parts, bonding of some sort, and verification that secure attachment has been made. Most large space structures will require some assembly.

In many cases, a structure can be most compactly transported in the form of feedstock, with the fabrication of components from the feedstock accomplished in space. The best example of this technique is an automated beam builder which uses rolls of aluminum strip stock to produce long, triangular cross section beams. The elements of the beam are produced by roll forming the aluminum strip, and the cross members are attached by an integrated ultrasonic welding device. The beams thus fabricated can then be assembled into a larger structure. In most cases, the cost of fabrication and assembly will contribute a high percentage to the final cost of a very large space structure. Fleisig [27] has done a detailed pilot study of the fabrication and assembly of a small space platform from a single shuttle load (see section).

Maintenance will also have to be performed on space structures. This may include repair of faulty joints, repair of components, replacement of parts, and additions and modifications to a structure.

The need to deploy, fabricate, assemble, and maintain large structures requires the capability for manipulation of large physical objects in space. There are three possible agents that can accomplish such tasks: humans in spacesuits, teleoperators, and robots. We will briefly examine all three possibilities, focusing on robots as the best alternative.

4. Teleoperators

One way of accomplishing the space construction and maintenance tasks outlined in the previous section is by using humans in spacesuits (EVA or extra vehicular activity). An alternative is to employ teleoperators. A teleoperator is a manipulation system that is remotely controlled by a human operator in response to sensory information such as a TV picture of the workplace [54]. Examples range from the primitive mechanical claws used to handle radioactive materials to an arm with a shoulder, elbow, wrist, and five-fingered hand, controlled by the operator's arm in a gloved sleeve, and including force and tactile feedback [7].

4.1 Advantages

The advantages of employing teleoperators for manipulative tasks as opposed to using people directly are reduced costs in hazardous or remote environments and improved performance by scaling size and forces up or down.

Examples of operations requiring manipulative capabilities in hazardous or remote environments include those in nuclear power plants, underground mining [4], exploration and mining on the ocean floor [70], and space applications. Replacing humans with teleoperators in these operations eliminates the direct costs of transporting people to these environments and maintaining them there. For example, it is estimated that the cost of maintaining a single person in space for a year is $2 million [33]. This includes the extra payload of 5000 kilograms per year of air, food, and water that the average person consumes. It does not include the extra fuel that must be carried due to the constraints that human cargo place on temperatures and G-forces.

In addition to the direct costs of using people in hazardous environments, there are the indirect costs associated with the required fail-safe nature of support systems. These penalties appear in the form of increased costs and decreased performance. For example, the productivity of underground coal miners was cut almost in half over the last 10 years, principally due to increased OSHA regulations designed to make the occupation safer [4]. In space, it is estimated that an astronaut can safely perform only one or two hours of zero-G extra vehicular activity during each 24 hour period [33].

The second advantage of teleoperation over direct human manipulation is the potential for improved performance by scaling size and force. A teleoperator which magnifies human reach and strength would be required to manipulate the components of a large space structure. Similarly, by scaling down the size, motions, and forces of a surgeon's hand, a teleoperator could be used to perform microsurgery with improved access and precision.

4.2 Space Applications

There are many potential applications of teleoperators in the space program. The utility of a teleoperator for performing the space construction tasks described in the previous chapter should be obvious. Indeed, such large scale operations would not be feasible without extensive use of teleoperators. In addition, the large, complex satellites required for advanced applications will require deployment, retrieval, and in-orbit servicing, jobs ideally suited to teleoperators. For example, deployment of the ATS-V satellite accidentally left it spinning; a subsequent simulation study concluded that a free-flying teleoperator could dock with the

satellite and despin it using reaction jets (see section). Finally, teleoperators could be used to perform space rescue missions, a need that will increase as more applications involving people in space are developed. For example, a readily available teleoperator may have been able to ameliorate the dangerous situation that developed on the Apollo 13 mission after an on-board explosion.

4.3 Taxonomy of Space Teleoperators

Space teleoperators can be classified as free-flying, rigidly attached, tethered, or surface based. The most flexible but most complex teleoperator would be a free-flying vehicle with reaction jets for propulsion and maneuverability. It would be the logical choice for general purpose orbital operations. A much simpler system is a device that is firmly attached to a reference base. An excellent example is the space shuttle manipulator arm which is used to deploy and retrieve shuttle cargo [24]. More flexibility is obtained with a tethered teleoperator. Criswell [17] describes a "space spider" assembly machine that could navigate the two dimensional surface of a structure by paying out or taking in cable on several radially placed tethers. Surface teleoperators include both fixed and roving vehicles designed for the surface environment of a moon or planet. The Viking Mars lander employed a teleoperated arm for collecting samples. A proposed 1984 unmanned mission to Mars included plans for a roving teleoperator [49].

4.4 Survey of Teleoperator Technology

The purpose of this section is to describe the range of technologies that are relevant to teleoperator design. All teleoperators incorporate three main functions: sensing to relay information about the workplace to the operator, manipulation to carry out the actions of the operator at the workplace, and man-machine communication in order to present the sensory information to the operator in a form that is meaningful and readily assimilated and to allow the operator to express his actions in a natural and effective way.

4.4.1 Sensing

Teleoperator sensors include both imaging devices to give an overview of the workplace and special purpose sensors located on the end effectors of the manipulators to allow activities requiring high precision.

Image systems may consist of a single camera or may incorporate multiple camera views. The cameras may be black and white, color, or may sense other regions of the spectrum such as ultraviolet or infrared. Distance information may be obtained from a stereoscopic pair of cameras or directly from a laser range finder.

Manipulator terminal sensors include a device for indicating the proximity of an object by the interruption of a light beam between a source and a detector. Touch and slip can be detected by arrays of tiny pressure pads. Piezo-electric crystal transducers can be used to measure force and torque.

4.4.2 Manipulation

The most important characteristics of a manipulator are its physical dimensions, its configuration and degrees of freedom, and its end effectors. The geometric dimensions of a manipulator include the size of the

workplace it can reach, the size of the objects it can handle, and its positioning accuracy. The configuration deals with the number and types of joints, such as hinged, rotary, or ball and socket. Manipulators typically exhibit six degrees of freedom: the three axes each for position and for orientation. The end effectors of a manipulator are vitally important and range from general purpose "hands" for grasping to special purpose tools such as arc welders.

4.4.3 Man-machine Communication

Conceptually, a teleoperator incorporates two man-machine interfaces: that between the sensors and the operator and the one between the operator and the manipulators. The human engineering of these interfaces is critical for effective use of the teleoperator. The simplest systems include graphic displays for image data, audible signals for proximity or touch sensors, and joysticks for controlling the manipulator. A much more natural method for controlling an arm-like manipulator, designed at JPL [7], uses a sleeve and glove worn by the operator. The arm duplicates the motion of the sleeve and relays direct force feedback to the sleeve in the form of resistance to the operators motions. Future systems will include speech synthesis for conveying information to the operator and speech recognition for interpreting commands from the operator. Systems must also be designed for aiming sensors, such as a camera controller which responds to the head or eye motions of the operator.

An advanced man-machine communication system is proposed by Criswell [16] to deal with teleoperator applications which involve a significant time-delay in the feedback loop between operator and manipulator. His "projective teleoperator" system would use a computer to simulate the effects of operator actions and immediately display the predicted effect to the operator. The display is then continually updated to correspond to the actual sensory data received from the remote site, but with a time delay.

4.5 Limitations of Teleoperators

Note that a pure teleoperator has no autonomy; it is totally dependent on its human operator. This section discusses some of the limitations of this scheme and proposes greater automation of teleoperator functions as a solution. The limitations of the pure teleoperator approach include communication time delays, limits on information flow, human costs, and human performance limits.

4.5.1 Communication Time Delay

The speed of light introduces a significant time delay in the transmission of information over the long distances common in space communications. For example, the round-trip transmission time from the earth to geosynchronous orbit and back is .3 seconds, for the moon it is 2.6 seconds, and Mars is from 10 to 40 minutes away, depending upon the relative positions of earth and Mars in their orbits. It has been found empirically that one tenth of a second is the maximum tolerable time delay for continuous closed loop control of a complex task. Thus, a distance of 20,000 kilometers or more requires a "move and wait" control strategy [21]. This results in large inefficiencies in the operation of remote vehicles. For example, it is estimated that a purely teleoperated Mars rover could perform useful functions only 5% of the time, the remaining time spent waiting for instructions from earth. A similar rover with a significant degree of autonomy built in could operate 80% of the time. In addition to efficient operations, there are some applications, such as the descent

engine control of the Viking Mars lander, that require real-time control. Finally, potential hazards in an uncertain environment often demand rapid response. For example, a Mars rover in the path of a landslide that it accidentally triggered could not wait for instructions from earth to decide what to do.

4.5.2 Limits on Information Flow

In addition to the time delays, there are limitations on the amount of information that can be communicated between the earth and a space teleoperator. These limits apply both to transmission of data from the teleoperator and transmission of command information from earth. The reasons for these limits include bandwidth constraints, interference problems, and poor signal to noise ratios. In addition, a teleoperator is likely to have a limited power supply, and communications must compete for power with the rest of the vehicle functions. Probably the most important information flow constraint is total communication blackouts due to the interposition of the earth, moon, or sun in the transmission path. For example, continuous communication with a satellite in low earth orbit requires a network of ground stations distributed around the globe, communication with the far side of the moon is impossible, and communication with Mars is interrupted when Mars is on the opposite side of the sun from earth.

4.5.3 Human Costs

Probably the most important reason for automating teleoperators is to reduce human costs on the ground. In spite of its expensive space hardware and sophisticated ground support systems, NASA's largest expense is people. It has been estimated that as much as 90% of mission costs are associated with human productivity on the ground [29]. Furthermore, 25% of NASA manpower is devoted to some aspect of computing [73]. A NASA study [66] estimates that automation of spacecraft and ground systems could achieve a 100 fold reduction in mission support costs by the year 2000. This amounts to a $1.5 billion per year savings. Such cost reductions are especially important for making long range, multi-year missions practical.

4.5.4 Human Performance Limits

Since pure teleoperators are directly controlled by humans, their design and functionality are primarily anthropomorphic. The result is that they are subject to many of the limitations of their human operators. Some of those restrictions are physical, such as the fact that a human operator can effectively control only two manipulators and can directly make sense of electromagnetic waves only in the visible light spectrum. Other limits are mental; people have slow reactions, can only concentrate on one task at a time, and have severe limits on the amount of mental complexity they can handle at one time. This makes it difficult for humans to control the increasingly sophisticated subsystems found on spacecraft, such as intelligent instruments. Furthermore, the qualitative physics of the space environment is likely to be counter-intuitive to the untrained human operator. As a result, straightforward operations that must be performed repeatedly and with a high degree of reliability, such as spacecraft attitude control or routine construction, are probably better suited to machine rather than human control.

Due to the above limitations of teleoperators, we consider robots as an alternative solution to the problem of manipulation in space.

5. Applications of Space Robots

Robots are immune to most of the limitations of teleoperators described in the previous chapter. As a result, there are several space applications for which robots are particularly well suited. These robots include a deep space probe, a lunar or Mars rover, an earth orbiting robot used for satellite maintenance and repair or space construction, and a space rescue robot.

5.1 Deep Space Probe

One possible application of robotics in space is the automation of scientific probes. Deep space probes represent the most compelling requirement for autonomous operation since speed of light delays preclude teleoperator control. This application is also somewhat simpler than the others since a flyby probe has no manipulation or locomotion requirements. A good example of such a mission is the Galileo Jupiter probe which is scheduled to fly in 1985 [31]. The spacecraft will make repeated close flybys of the Galilean satellites and will release a probe into Jupiter's atmosphere. This mission and others like it offer many opportunities to exploit currently available artificial intelligence technology.

5.2 Lunar or Mars Rover

Another space robot concept is that of an autonomous roving surface vehicle to explore the moon or Mars. Apollo 15 and 16 made use of a mobile 4-wheeled vehicle driven by the astronauts. The Soviet Lunokhod [56] mission explored a 2 km by 150 m area on the moon with an unmanned 8-wheeled rover teleoperated from earth by 5 operators using a direct open loop control strategy. A proposed 1984 Mars sample return mission [49] included as a key component a roving vehicle with a limited amount of autonomy to be operated in a supervisory controlled fashion. Even though it was cancelled due to budgetary considerations, the incorporation of advanced machine intelligence could make this a viable and cost-effective mission in the future.

The rover was expected to have 3 different modes of operation. In site investigation mode, the vehicle would be stationary and concerned with sample acquisition, manipulation and internal distribution. In survey traverse mode, the rover would cover 500 meter legs with autonomous route plotting using a laser ranger or stereo imaging system. Reconnaissance traverse mode was designed for few stops or science experiments but would enable the vehicle to traverse through the night and would allow over 1000 kilometers of terrain to be surveyed in the course of a mission.

According to the NASA Machine Intelligence and Robotics Study Group [66]:

> The scenario of a semi-autonomous craft with on-board problem solving intelligence and a symbolic model of its own capabilities might go as follows. Scientists decide that a sample of reddish material spotted about 15 meters away should be analyzed by science package 21. Using graphics techniques, they draw an outline around the sample on the TV image. Using this outline to identify the object of interest, the on-board vision system converts the image data to coordinate data in its local coordinate frame. The vision system issues the goal of causing a piece of the sample located at the coordinate to be transported to the input hopper of science package 21, located at another known position. The navigation problem solver then generates a course, moves

the craft to within arm's distance of the sample, reaches, grasps, then verifies visually and by tactile feedback that a red mass exists in its grasper. It then plans an arm trajectory to package 21's input hopper, noting that the flap of package 13 is up, and must be avoided. After moving the sample to the hopper and ungrasping, it visually verifies that a red mass exists in the hopper, and no longer exists in the grasper. It turns on package 21, and reports back to ground.

5.3 Earth Orbiting Space Robots

While speed of light delays provide the primary motivation for the automation of a deep space probe or a Mars rover, there are important applications for space robots in earth orbit as well. These include satellite servicing and space construction.

5.3.1 Satellite Servicing

Satellite servicing provides several applications for space robots including deployment, maintenance, repair, and retrieval. Deployment involves removing a satellite from the shuttle cargo hold, precisely positioning and orienting it, extending any compressed structures such as solar panels or antennas, and performing any initialization tasks required to make the satellite operational. In the future, complex satellites may be designed to take advantage of periodic maintenance to be performed by space robots. Satellite repair, by even such simple mechanisms as replacement of faulty circuit boards, could greatly extend the lifetime of future satellites. In the case of a complex failure to an expensive satellite such as a spacelab, the satellite could be retrieved from orbit, placed in the shuttle hold, returned to earth for servicing, and then relaunched in the shuttle.

Several in-depth studies have been done on the feasibility of various satellite servicing missions. Cardall and Moller [12] did a simulation study of a mission to use a ground controlled teleoperator to dock with and despin a satellite. In 1969, ATS-V was launched and due to a series of unexpected and improbable conditions, the satellite was left spinning upside down about its symmetrical, stable spin axis. The requirements of the teleoperator system include a docking cage and latches that can be spun up to the spin of the satellite, a video system and lamps to illuminate the satellite, and an attitude control system consisting of dual purpose gyros which both sense attitude changes and react to correct them. The different stages of the mission include launch, pre-contact docking, post-contact docking, despin, separation, and observation. The conclusion was that the mission could be accomplished with a high probability of success. However, the reason is that fortunately the ATS-V is spinning along the same axis as its docking receptacle.

The more general problem of how to capture and "passivate" or stop the motion of a satellite freely tumbling along all three axes is addressed by Kaplan and Nadkarni [42] from a mathematical point of view. They divide the task into five stages. First, the robot must rendezvous with the satellite in the sense that the relative translational motion between the two bodies must be cancelled out. Then, the satellite must be observed to determine its motion along all three axes. Next, the satellite must be grasped, resulting in a new body which consists of the satellite plus the robot. Note that the mass of the satellite may be unknown. Torques must then be applied by the robots thrusters, which will have limited directional freedom, to passivate the two body system. The authors go into the mathematical details on the torques necessary to passivate such a system. Finally, the robot and satellite must be translated to the target location.

Criswell and Ayres [16] look into the applications of robots for satellite repair. Failure modes are classified as wearouts, random failures, and design flaws. The service scenario they present consists of the servicer docking with the satellite, removing a faulty module, and replacing it with a properly functioning module. An economic analysis shows that in order for satellite repair to become cost effective there must be modularization and standardization of satellite designs. In addition, it must be possible to create less expensive, more reliable, and more flexible spacecraft by utilizing in-space servicing.

5.3.2 Space construction

A second major application of robots in earth orbit is space construction. This includes the assembly of such structures as a solar power satellite, large antennas, a space station, or space manufacturing plants. Criswell [17] outlines some of the requirements for a general purpose construction unit for use in space.

Fleisig [27] presents a detailed study of an initial "Shuttle demonstration of large space structure fabrication and assembly." Based on a set of representative structures including a 180 meter radiometer, a 120 meter solar array, and a 110 meter night illuminator, a demonstration article was designed. It consists of a 31.5 meter long space platform with three identical bays, and is similar to a scaled down version of the space operations center proposed by Covington and Piland [13]. One of the design considerations for the platform is deformation due to temperature gradients, which are greatest when one part of the structure is in the shadow of another part. In addition, it must withstand the loads from the shuttle reaction control system, taking into account the structural dynamics of the rigid shuttle coupled with the flexible platform.

The structure is composed of 23 beams totalling 267 meters and 12 joints. The beams are fabricated by the beam builder and can be carried in one shuttle load. The ends of the triangular beams are fitted with tripod assemblies. The node joints could be either ball and socket or probe and drogue mechanisms. The construction task employs the shuttle remote manipulator system and two astroworkers (EVA) in addition to a regular shuttle crew. Using an assembly fixture, the structure emerges from the shuttle cargo bay. It is estimated that the task would require 115.5 man-hours over a total of 38.5 hours and could be accomplished in a 7 day shuttle flight. An excellent experiment to test the use of robots in space construction would be to replace the two astroworkers with robots in this scenario.

5.4 Space Rescue

Space robots provide an opportunity to quickly and cheaply mount rescue missions to save human lives and salvage expensive machinery from space in the event of unforeseen circumstances. Several rescue robots could be maintained at minimal cost on standby either on the ground or in low earth orbit. There have been several situations in the recent history of the U.S. space program that could have taken advantage of this capability. These include the explosion aboard Apollo 13 and loss through reentry of the Skylab Space Station.

In order to assess the feasibility of these applications, we must examine the state of technology in the various component systems that must be included in a space robot in order to accomplish these tasks.

6. Component Systems

The component systems that would be required by a space robot, include manipulators, sensors, navigation, guidance, propulsion, surface locomotion, computing and control, communications, electrical power, and spacecraft structure. For each system, the requirements of the various robot scenarios are described, the current state of the art is assessed, and the important outstanding research problems are identified.

6.1 Manipulator Systems

Since it never comes in contact with any foreign objects, a deep space probe is the only space robot with almost no manipulation requirements. On the other hand, a lunar or Mars rover must be able to scoop or pick up a sample, turn it around for different camera views, and reject or place the sample in the proper bin for analysis or storage for return to earth. All forms of in-space satellite servicing require the ability to dock with the satellite. Special purpose docking refers to docking with standardized receptacles such as a ball and socket mechanism or a probe and drogue setup. General purpose docking involves docking with a non-standard device or some other object. Note that undocking must also be done with care to avoid imparting any linear or angular momentum to the satellite. In addition to docking, a satellite servicing robot must be able to attach to, remove, and replace a faulty module. The primary manipulation requirement for space construction tasks is the maneuvering and attachment of beams, which calls for large and powerful arms. In addition, the joining task requires at least two manipulators, even though one may only need a few degrees of freedom.

The current state of the art in space qualified manipulators is the Shuttle Remote Manipulator System, designed and built in Canada [24]. The manipulator is fixed to the front of the shuttle cargo hold and its primary tasks are payload deployment and retrieval. The arm consists of a shoulder with two degrees of freedom, a single degree of freedom elbow, and a wrist with two degrees of freedom. It has a 15 meter range, a maximum workplace extension of 4.6 by 18.3 meters and can handle the full shuttle payload capacity of 30,000 kilograms. The end effector has six degrees of freedom and the accuracy of the system is plus or minus 5 centimeters. Note that in general, manipulators are limited to three orders of magnitude in the ratio of workplace extension to positioning accuracy [7]. The shuttle manipulator takes advantage of the zero gravity environment it was designed for to the extent that it can't hold its own weight in earth's gravity. The manipulator can be directly controlled by a single operator using two joysticks, switches, or a keyboard. The operator views the workplace directly through windows and also indirectly through closed circuit TV cameras. Alternatively, the system can be operated in automatic mode, either by moving between operator generated endpoints or by following predetermined trajectories. Both manual and automatic control modes must take into account the many interactions between the orbiter, its reaction rockets, the arm, and its payload. These include orbital mechanics, plume impingement, and reaction forces, problems not normally encountered in earth-bound manipulator systems. In addition, the natural frequencies of the arm must be actively damped out. The first flight test of the manipulator in November 1981 was quite successful.

Current research in manipulator systems falls into three categories: actuators, end effectors, and adaptive sensor referenced control.

The actuators of a manipulator are the components that cause it to move. The current state of the art in this area is a servo controlled electric, hydraulic, or pneumatic motor for each joint either physically located in the joint or located elsewhere with the power mechanically transferred. The accuracy of these systems must be refined and other systems developed. One possible candidate currently in the research stage is a joint that is remotely actuated with cords or "tendons" [38]. Another research area is that of direct drive motors utilizing certain rare-earth elements [2].

Since a manipulator only positions its end next to some object, the actual work must be performed by some end effector or tool. The most general end effector is a grasper and the design of dextrous "hands" is the subject of much current robotics research. However, for specialized or repetitive tasks such as those required for space construction, it is simpler and more effective to fit the manipulator with a dedicated tool. Joining devices include electron beam, laser, and arc welders, and mechanical riveters. Cutters, trimmers, and grinders will also be needed. Finally, surfaces will have to be treated either by vapor deposition or with paint [17].

The fundamental research problem of robotics is that of adaptive sensor referenced control, or how to automatically control a manipulator in response to external sensory input.

Manipulation can be divided into two phases that require roughly equal amounts of time but pose quite different problems. The first is terminal positioning and orientation and the second is dynamic accommodation and compliance [7]. For example, in the task of inserting a peg into a hole, the first stage would involve bringing the peg near the hole while the second stage would have as its goal actual insertion of the peg into the hole.

There are two different techniques for accomplishing the second stage, which ideally are used in conjunction. Dynamic accommodation refers to using sensors located on the end effector in a tight feedback loop to actively refine the position and orientation of the end effector. Passive compliance utilizes an end effector with limited freedom of movement in order to passively respond to local forces. Dynamic accommodation and compliance are still research problems.

Control modes for a manipulator can be divided into three potentially overlapping classes: manual, program controlled without feedback, and sensor referenced. Totally manual control is the mode employed in a pure teleoperator. The research problem here is one of man-machine communication. Program control without feedback is used in almost all industrial robots and is well understood. It involves following a series of endpoints or paths that are preprogrammed. The key research area is computer control referenced to external sensor input. This is the control mode required by a space robot.

Control tasks can be classified by levels of complexity. The simplest task is path traversal, or going from one point in space to another, subject to velocity constraints. This involves solving the dynamic equations for each joint of the manipulator; the research issue is how to do it efficiently. Partial table lookup techniques [38] allow one to trade space for time in this problem. More complex than path traversal are tasks like the sample acquisition scenario described in the previous chapter. These tasks can be accomplished by incorporating in the control loop image and range sensors and terminal and compliance sensors on the manipulator. More complex activities such as satellite or structure repair and automatic assembly require computer based planning and problem solving techniques that are still in the research stage.

6.2 Sensors

Smart sensors are a vital component of any space robot. These include sensors for scientific data collection, ranging devices for determining the distance to an object, imaging techniques for obtaining a picture of an object or environment, and terminal and compliance sensors to aid in manipulation.

6.2.1 Scientific Data Collection

One of the primary purposes of sensors on spacecraft is to gather data that has scientific value. Some of the major sources of such data are wave and particle phenomena such as visible, ultraviolet and infrared light, electromagnetic spectra, gamma and X-rays, cosmic rays, gravity waves, and magnetic fields. In addition, those planets with atmospheres (Venus, Earth, Mars, Jupiter, and Saturn) call for various kinds of atmospheric analyses including temperature, pressure, and composition of the gases. Finally, samples obtained from landing probes must be examined to determine physical, chemical, and possibly biological makeup.

A detailed examination of the state of the art in each of these specialized types of sensors would be outside the scope of this paper. The research issues in general involve improving accuracy or resolution in the presence of severe size, weight, power consumption, and reliability constraints. In addition, new types of sensors need to be developed and space qualified.

6.2.2 Rangefinding

Accurate rangefinding is required for docking and positioning with respect to other objects. Rangefinding techniques can be divided into two classes: time of flight mechanisms and triangulation methods.

Time of flight techniques are based on the concept of sending out a signal to bounce off an object and timing its return, hence determining the distance to the object. Its principal manifestation in space applications is radar (sonar is quite useless in space). Radar systems fall into two categories depending upon the frequency of the signal: microwave and optical (laser) radars. Microwave radar is a well developed technology and is accurate to within 3 meters throughout the solar system. Optical systems offer the promise of greater accuracy due to higher frequencies and also can be used to find objects that are transparent to microwave frequencies. Laser radars include galium arsenide (GaAs), yttrium-aluminum-garnet (YAG) and CO_2 devices. The CO_2 laser operates at 15% efficiency and requires 25 to 150 watts of power for a 20 kilometer range. Even though they are still in the research stage, optical radars are expected to become competitive with microwave systems for space applications [20].

A primary application of radar systems is in docking. Docking can be classified as cooperative or non-cooperative depending on the target. A cooperative target is one equipped with a radio or optical beacon, a transponder, or a reflector to aid the docking process. Current radar ranges for microwave systems are 70 kilometers for non-cooperative and 600 kilometers for cooperative docking. The corresponding ranges for optical radars are 20 kilometers and 200 kilometers, respectively [20].

Triangulation is another technique for finding the distance to an object. It is based on having two devices a known distance apart and accurately measuring the angle between the baseline and the object for each device. Triangulation methods can be divided into passive and active illumination schemes.

The principle passive illumination method is stereo vision: extracting depth information from two different views of the same object taken by two different cameras separated by a baseline [47]. This involves first selecting a prominent feature point on the object. Next, the two images must be registered to identify the same point in both views. Finally, the effective camera angles are determined from the coordinates of the pixels and the depth is computed. Multiple distance measurements can be made from the same pair of images.

Active illumination techniques, such as a laser rangefinder, avoid the difficult problem of image registration. A laser rangefinder [41] has a camera at one end of its baseline and a scanning laser beam at the other end. The laser directs its spot of light at a point on the object whose distance is to be measured and directly determines the angle from the scanning mechanism. Meanwhile the camera easily detects the single spot of light and determines the effective angle from the pixel it falls on. By synchronizing the scanning laser beam with the camera, multiple depth measurements can be made. Active illumination methods have the advantage of working under conditions of little or no ambient lighting. They have the disadvantages of limited range and limited numbers of samples.

6.2.3 Robot Vision

In addition to scientific data collection, television imaging is required by a robot for manipulation, especially in the terminal positioning and orientation phase. Robotic vision differs from the classical computer vision problem in two important respects. First, the images are not static but changing, and second, the analysis must be done in real time, which for television is 30 frames per second. Vision systems can be broken down into three stages: the camera, feature extraction, and scene analysis. Much of this material is from [74] which describes an experimental robotic vision system developed at JPL.

The first phase of any vision system consists of the camera. There are two candidate technologies: TV camera tubes, of which the vidicon is a prime example, and solid state sensor arrays, exemplified by the CCD (charge coupled device) camera. Even though they represent a relatively new technology, solid state cameras are expected to entirely replace vidicons for space applications due to their superior size, weight, power consumption, and reliability characteristics [48].

The most important parameters of a camera are resolution, geometric fidelity, spectral response, sensitivity, and dynamic range. Resolution is the number of picture elements, or pixels, per image and is currently about 512 by 512 for both tube and solid state cameras. Geometric fidelity refers to the amount of spatial distortion in the image. The very high geometric fidelity of solid state cameras is one of their chief advantages over tube cameras. Spectral response is the frequency bandwidth that the camera can detect, such as visible light, ultraviolet, or infrared. Sensitivity refers to the amount of illumination required for successful operation of the camera. Finally, dynamic range is the number of bits per pixel that the camera can distinguish. One factor that greatly influences the number of bits is the choice of black and white versus color cameras. An experimental study of vision systems for teleoperators [28] found that a color camera does not significantly improve operator performance and that two different black and white views are superior to a single color view.

Given an analog signal from the camera, the signal must be digitized by an analog to digital converter, the information must be stored in a memory, and access must be provided to the processing computer. Ideally,

these functions should be continuous, concurrent, and non-interfering. The most common technique for achieving this is a frame buffer, which is simply a random access memory in which each address corresponds to a single pixel of the image.

The next stage of processing in a vision system is low-level feature extraction. This is normally accomplished in four phases: segmentation, edge detection, edge clustering, and chain coding. Segmentation involves separating the image into regions with common color and brightness. Edge detection is the process of finding discontinuities of brightness in the image that may correspond to lines or outlines of objects. This is done by first taking the spatial derivative of intensity of the image to produce a gradient image. The value of a pixel in the gradient image is proportional to the rate of change of the intensity at the same point in the original image. By thresholding the gradient image, setting all pixels below a certain threshold to zero and the rest to one, a binary edge map is obtained which indicates the edges in the image. This entire edge detection process can be done in hardware by a special purpose pipelined processor in order to achieve the high speeds necessary for real time processing.

Since the edges in the binary edge map are typically short, discontinuous segments with non-uniform orientations, they must be clustered into smooth continuous curves to generate the actual edges of objects in the image. Finally, the data in the bit map of smoothed edges must be compressed into a more economical data representation. One such representation is a chain code which describes a boundary by giving, for each pixel on the boundary, the direction of the next boundary pixel. Since there are only eight possible adjacent pixels in a rectangular matrix, the chain code can be stored in three bits per boundary pixel. This representation also facilitates edge traversal, a common operation in the next stage of vision processing.

An alternative to the edge detection paradigm for feature extraction is region growing. This technique starts with a pixel and coalesces as part of the same region any neighboring pixels with the same color or intensity, until the image is partitioned into a set of such regions. Next, adjacent regions with similar color or intensity are clustered together to obtain a set of objects.

Several of the low-level image processing tasks provide information that can be automatically fed back to control other aspects of the vision system [26]. For example, once an object of interest is found in the image, a window can be drawn around the object and all further processing will only occur within the window. The camera aperture can be automatically adjusted based on the maximum pixel intensity in the window. Finally, the camera focus can be adjusted to maximize the intensity of the gradient image in the window, which corresponds to sharpening the edges. The resulting focal length gives a rough estimate of the distance to the object.

The final stage of computer vision is the most difficult and is known as pattern recognition or scene analysis. The goal of this phase is to obtain a high level symbolic description of the image in terms of objects and their relation to one another. This requires that the vision system have some kind of knowledge about what kinds of objects it can expect to see. Hence, the problem becomes one of matching the features of the image to features of objects the system knows about.

The two most common approaches to this problem are template matching and feature discrimination. In template matching, the chain code of the image is matched against a set of templates of possible objects in terms of lines and arcs and their relationship, and the best match is selected. Feature discrimination involves

computing a set of higher level features such as average brightness, center of mass, area, perimeter, and line thickness, and matching them against a set of corresponding feature vectors for known objects.

Pattern recognition, scene analysis, and other high-level vision processing, such as shape and texture determination, are currently active areas of research in artificial intelligence and more work is still needed in order to build production quality systems.

6.2.4 Manipulator Terminal Sensors

The last category of sensor systems to be considered are manipulator terminal sensors that are needed for the dynamic accommodation and compliance phase of manipulation. These fall into three classes: proximity, touch/slip, and force/torque sensors [34]. This is an area where much research is still needed.

Proximity sensors are used to discern when the end of the manipulator arm is almost in contact with some object. The basic mechanism used is a set of light sources and photo cells to detect either interruption or reflection of the light beams. Ideally the sensor should work along all three axes. Such a proximity sensor has been built for a shuttle sized manipulator [7].

Touch and slip sensors are useful for picking up and handling objects. One promising technology utilizes carbon doped silicone rubber which has the property that its conductance changes with pressure. A resolution of 100 detectors per square inch of sensor surface has been achieved with this material [62]. Using a matrix of wires, a high resolution touch sensor with spatial resolution of 256 points per square centimeter has been developed at M.I.T. [75].

Force and torque sensors are required for effective manipulation once an object has been grasped. Piezo-electric crystal transducers can be used to measure forces and torques directly at the end effector. These detectors can operate in a range of forces from .5 to 300 Newtons. In addition, force or torque can be measured at each of the manipulator joints by sensing electric current or hydraulic or pneumatic pressure. Force and torque sensing along all three axes has been investigated for handling large objects.

6.3 Navigation, Guidance, and Propulsion of Free-Flyer

Navigation, guidance, and propulsion are essential functions of a free-flying space robot. Navigation is defined as the precise determination of the position, velocity, and attitude or orientation of a vehicle at a given instant in time. Guidance is concerned with methods for altering the position, velocity, or attitude of a craft. Propulsion is the principal means of guidance for spacecraft.

6.3.1 Navigation

There are several different types of navigation requirements for spacecraft. The first and most obvious one is to be able to accurately navigate to some mission destination. In addition, many spacecraft require precision pointing and control of antennas, sensors, solar panels, etc., thus necessitating attitude adjustment and maintenance. Finally, for any earth orbiting satellite collecting and transmitting data, all three navigation parameters of the satellite plus time are an essential part of the data.

The current state of the art in space navigation and guidance is described by the accuracy that can be achieved in delivering a spacecraft to a target destination. For planetary flyby missions, 50 to 100 kilometer accuracy can be achieved for the inner planets while the outer planets can be encountered with a precision of 100 to 1000 kilometers. Spacecraft can be injected into specific orbits around planets such as Jupiter with an accuracy of 50 kilometers. Planetary landing probes such as the Viking Mars lander can achieve an entry corridor angle with an accuracy of 1 degree and land within 100 kilometers of their target. Finally, the current state of the art with respect to the precision of earth satellite orbits is 10 meters. This figure is expected to shrink to between 2 and 20 centimeters by the year 2000 [20].

There are various different methods for space navigation. However, any navigational model must account for several important factors, including variations in the earth's rotation rate, the precession of the rotational axis, the gravity structure of the earth or other target bodies, atmospheric effects on radio signals, and forces on the spacecraft caused by gas leaks. In addition, most models are particularly sensitive to errors in tracking station locations and errors in the position of a target planet [40].

The principle method of spacecraft navigation is the use of radar and doppler shift to track the craft from the earth. Radar can measure the distance to a spacecraft with an accuracy of 3 meters out to the limits of the solar system. Doppler shift allows the determination of velocity to a precision of 1 millimeter per second over the same range [18]. Note that this system is totally earth based, all computation is done on mainframe computers on earth, and the spacecraft does nothing more that passively reflect radio signals.

In contrast, the NAVSTAR Global Positioning System uses a set of navigation satellites to enable earth orbiting satellites to do their own navigation entirely on-board. Accuracy estimates for the system are 2 to 5 meters for position, 1 to 5 centimeters per second for velocity, and 5 to 10 nanoseconds for time [40].

There exist navigation techniques which do not require tracking stations or satellites for reference points. Principle among such self contained methods is the inertial navigation system. This scheme utilizes three gyroscopes spinning around mutually orthogonal axes to directly and accurately detect all accelerations of the vehicle. By integrating the accelerations over time, velocity and position are obtained. While very effective over short distances, purely inertial systems are of limited use for long duration missions since there is no reference to the environment and small errors accumulate rapidly.

In the long run, the future of space navigation lies with Onboard Automated Optical Navigation (AON). In this system, the spacecraft uses a CCD or other solid state camera to take a picture of a planet or other target body relative to the fixed star background and directly compute its position from this information. This system has the advantage of being completely self-contained and accurate over any range or mission duration. However, it is still in the research stage [40].

6.3.2 Guidance

Guidance is concerned with altering the position, orientation, or velocity of a spacecraft to satisfy the objectives of a mission. Orientation, or attitude, is most effectively adjusted and maintained by storing angular momentum in three orthogonal gyroscopes and transferring it to the spacecraft by braking or accelerating the gyroscopes. Using this technique, the Multimission Modular Spacecraft (MMS) attitude control system is designed to yield accuracies of 8 to 15 arc-seconds [40].

Spacecraft position is altered with the use of rockets (see "propulsion" below). An important consideration for positional guidance in low earth orbit is the fact that vertical or latitudinal motion of more than a few hundred meters results in trajectories along different orbits. Hence, orbital transfer is involved in these maneuvers rather than simple straight line motion, and orbital mechanics is required to compute the precise direction and duration of rocket burns.

6.3.3 Propulsion

Some form of propulsion is required in order to change the position or velocity of a spacecraft. Propulsion systems can be divided into three types: chemical rockets, solar-electric drives, and nuclear reactors. Most of this material is from [22].

Chemical rockets are the only type of propulsion currently being used in space. They have two primary advantages. One is that the ratio of the mass of the propellant to the inert mass of the rocket is large. The second advantage is the low cost of the hardware and propellants. Large motors, providing thrusts of 100 to 400 Newtons, burn hydrogen and oxygen since these fuels provide the maximum chemical energy storage density. Thrusts of .5 to 250 Newtons are supplied by smaller rockets burning flourine and hydrazine.

Solar-electric motors convert solar energy to electricity and use the electricity to accelerate some propellant. For example, one design uses mercury propellant which is accelerated electromagnetically. Their chief advantage is that they use collected energy instead of relying on stored energy. Their primary disadvantage is that they are only useful in applications requiring low thrust, such as transfer from low earth orbits to high or geosynchronous orbits, or for interplanetary travel. Another disadvantage is that solar power is only useful within the inner planets. Solar-electric propulsion systems are still in the research stage.

Nuclear propulsion will become the system of choice in the long term due to the fact that nuclear fuel is the most efficient form of energy storage, by three orders of magnitude over chemical fuels. Hence, long, deep space missions will require some form of nuclear drive. However, much research is needed before a nuclear reactor can be developed for space propulsion.

6.4 Rover Mobility, Locomotion, and Guidance

Whereas the previous section dealt with navigation, guidance, and propulsion of a free-flying robot, this section is concerned with the corresponding problems faced by a roving surface vehicle. In this context, the major issues are path planning, mobility, and locomotion. Most of this material is drawn from [66].

6.4.1 Path Selection and Planning

Given initial and goal locations, a rover must be capable of plotting the best course from the initial point to the goal point subject to various constraints.

Path constraints are of three types: those imposed by the terrain, those resulting from energy considerations, and constraints based on the mobility and locomotion characteristics of the rover itself. Terrain constraints include boulders and ridges, ditches and crevasses, poor surfaces such as soft sand, and the

general slope of the terrain. In addition to terrain constraints, a rover is constrained by the requirement of conserving its energy resources to select minimum energy paths. In flat terrain this usually means following the shortest path. However, in hilly terrain, minimum energy paths follow contour lines, going through valleys and between hills. Constraints imposed by the rover's mobility characteristics will be discussed below.

There are several sources of information that can be used by a surface rover for path planning, including laser rangefinders, stereo vision, and maps of the surface.

A laser rangefinder gives accurate readings of the distance to nearby objects. However, it can't be easily used to recognize holes, surfaces, or slopes. Since it is limited in range and in the number of samples it can take, a laser ranger is most useful for very local obstacle avoidance requiring little look-ahead and only low resolution.

For medium range navigation and mapping with respect to landmarks, a stereo vision system is a very versatile information source. A roving vehicle can compare images of the same object taken from different places and hence use motion parallax to achieve very long baselines for determining distance information. The major disadvantage of a vision system is that it requires a great deal of complex processing.

For long range navigation, detailed surface maps are essential and can be obtained from orbiting satellites. Using maps introduces the problem of registering the vehicle's position with the map coordinates.

As the above section suggests, path planning must be done in a hierarchical fashion. Long range navigation must be done on a scale of many kilometers. Minimum energy pathways must be planned 100 meters to a kilometer in advance. In order to avoid impassable barriers it is necessary to look ahead 5 to 100 meters. Large obstacles can be avoided from a range of 2 to 5 meters. Small rocks and ruts must be dealt with on a meter by meter basis. Finally, actual pitching and rolling of the vehicle requires instantaneous response.

The problem of obstacle avoidance in path planning is an active area of research in artificial intelligence. Lozano-Perez [46] has presented a general and efficient algorithm for the abstract, perfect information version of the problem. His approach is to shrink the vehicle shape to a point, correspondingly expand the shapes of all the obstacles, and solve the simpler problem of a point navigating a field of transformed obstacles. McReynolds [51] describes a simple tree searching algorithm for path planning to be used by a planetary exploration rover. Hilare [30] is an autonomous, mobile robot being developed in France. Moravec [57] has built and successfully tested a mobile cart that uses a vision system to avoid obstacles in the real world.

6.4.2 Mobility and Locomotion

There are several different characteristics which together determine the overall mobility of a rover. One is the stability of the vehicle in terms of how many degrees of pitch and/or roll it can tolerate without overturning. Another is maneuverability, which is determined by the turning radius and dynamic characteristics of the rover. A third characteristic which affects mobility is the ground clearance of the body of the vehicle. Note that there is a tradeoff between stability and ground clearance and hence adjustable clearance is a desirable feature in a rover. The speed of a vehicle certainly is an important factor in its overall mobility. Perhaps the most important mobility characteristic of a roving vehicle is its method of locomotion. The primary candidates are wheels or tracks versus legged locomotion.

The advantages of wheels or tracks include the fact that they can achieve low footprint pressures for ultrafine sand or soft surfaces. At the same time, they provide good traction on hard surfaces. Wheels make it very easy to change directions. Tracks cannot turn as easily but can bridge larger trenches than wheels can. The control of wheeled vehicles is relatively simple. Driving each wheel at the same speed and steering angle is sufficient for smooth terrain. However, on irregular terrain, separate speed, torque, and strut position control may be required for each wheel.

6.4.2.1 Legged locomotion

Most proposals for legged locomotion involve 6 to 8 legs of varying joint complexity. The primary advantages of legged travel are exceptional maneuverability, high stability, the ability to handle very irregular terrain, and even the potential for climbing capability. The size of the feet of a legged vehicle represent a tradeoff between large feet for low footprint pressure and small feet for good purchase. The primary disadvantage of legs is that the dynamic control problem is complex. For example, the optimum gait, or sequence for moving the legs, changes depending on the terrain. In addition, the feet must be lifted over obstacles. Raibert [64] presents an extensive bibliography of legged locomotion.

6.5 Computing and Control

A space robot requires sophisticated computing and control for almost every aspect of its operation. Indeed, the level of complexity of the onboard control system is what distinguishes an autonomous spacecraft from the more conventional ground controlled craft. This section deals with the requirements, state of the art, and research needed in the area of computing and control for a space robot. Much of this material is from [66].

There are two types of requirements that must be considered. One is the functional requirements that must be satisfied by a computing and control system and the other is the operational constraints under which such a system must operate.

6.5.1 Functional requirements

The computing and control requirements of a space robot include control of all subsystems and individual experiments, machine intelligence, onboard data management, and man-machine communication for supervisory control.

Subsystem and experiment control is probably best handled by dedicating a small microprocessor to each subsystem or experiment. In contrast, machine intelligence tasks require fast, large scale computers with large memories. Examples of such tasks include planning and problem solving, scheduling and sequencing, decision making, pattern recognition, symbolic modelling, and mission monitoring.

Since a vehicle such as a planetary rover must acquire, store, retrieve, and manipulate large amounts of data, some type of onboard data management system is required. Data to be acquired and stored includes information as to the location, size, and composition of objects, and a model of the terrain. Data processing tasks include assimilation of this information into some type of semantic network and a mechanism for drawing inferences from the information.

A final requirement is a man-machine communication system to be used when the robot is being controlled in a supervisory mode from earth. This system must be capable of presenting the state of the robot and its environment in a form suitable to the ground controllers. Similarly, it must provide natural and effective mechanisms for issuing commands to the spacecraft.

6.5.2 Operational Constraints

The environment of a spacecraft imposes some unique operational constraints under which the computing and control system must operate. The most obvious constraints are on weight and power consumption; both must be minimized. The system must also be protected or shielded from radiation, temperature extremes, mechanical shock, and vibration. Another constraint is that the operation of the computing system must be entirely autonomous since there is no operator available. The most important constraint, and indeed the factor which has driven the development of spacecraft computers, is the requirement for extreme reliability. This aspect will be discussed in depth below.

The state of the art and research needs for spacecraft computing are described in terms of four areas: the underlying technologies, computer architectures, reliability, and space qualification of computers.

6.5.3 Computer technologies

The current state of the art in computer technology can be characterized by citing some figures of merit for semiconductor memories, bubble memories, active devices, and computer systems. Semiconductor memories currently can store 10^5 bits per square centimeter and this figure is expected to increase to 10^7 by 1990, doubling every 1.5 years. The cost of such memories is currently 10^{-2} cents per bit and should drop to 10^{-3} by 1990, halving every 2.5 years. Bubble memories with a density of 10^7 bits per square centimeter exist now and densities of 10^9 are expected by 1990. The data access rate for these memories is 1 megabit per second currently with an increase to 10 megabits per second anticipated by 1990. The density of active devices or gates has been doubling every 1.12 years, from 10^7 bits per square centimeter presently to 10^9 by 1990. The cost of these devices is now 1 cent per gate and should drop to .1 cents per gate by 1990. The speed of computer systems is currently 10^9 instructions per second, doubling every 1.5 years to 10^9 by 1990. The failure rate is halving every 2.75 years, from 10^{-15} bits per second presently to 10^{-16} by 1990.

Two new technologies on the research frontier are optical memories and superconducting systems. Optical memories will not become available before 1985 but in the long run offer significant advantages over bubble memories in density, cost, reliability, power consumption, and speed. Superconducting computers offer the advantage of very high speed. However, superconductivity has only been achieved below 4.2 degrees Kelvin, and even though this figure may increase to 35 degrees by 2000, the primary power consumer of such a computer would be the cooling system.

6.5.4 Computer architectures

The individual memories and processing units of a computer system must be integrated in order to fulfill the system requirements. This design is known as the computer architecture. Basically there are three candidate architectures for a spacecraft computer system: a set of distributed, dedicated microprocessors, a large centralized processor, or a distributed network of general purpose computers.

One of the advantages of the dedicated microprocessor approach is that it is well suited to a spacecraft with many small devices and subsystems, each with their own built-in intelligence and timing requirements. This architecture allows any space qualified microprocessor to be connected to the system. The relative independence of the processors allows simple interfaces between them that are easy to design, and the possibility of error isolation of particular processors. Similarly, software changes are localized, eliminating the need for extensive reviews or coordination. Finally, this approach should result in relatively short programs, which are easier to design, verify, and test. One of the disadvantages of the dedicated microprocessor architecture is that it is likely to require more total space, weight, power, and memory than necessary due to the fact that these resources are not shared. In addition, there is a distinct lack of flexibility. For example, in this scheme an intelligent device couldn't acquire any more memory then it was originally allocated.

These disadvantages can be remedied by the alternative architecture of a single, large, central processor. Among the advantages of this approach is that it supports time sharing and dynamic storage allocation, techniques that result in effective utilization of computing resources. It also makes available the large fast memories that are required for complex artificial intelligence tasks. A central processor allows software to be replaced with improved versions that may take up more memory. Finally, space, weight, and power are conserved since there is only one control logic. On the negative side, one of the disadvantages of a central processor is that its operating system is a large, complex program that is difficult to verify or test. Furthermore, any software changes require extensive coordination and testing. In addition, the scheduler must be capable of providing real time response to some subsystems.

The third candidate architecture is a distributed network of general purpose computers. In this scheme, any computer is able to handle any task and all the computers can communicate with one another. This architecture offers the *maximum* flexibility since all processors, memory, and peripherals are shared. It also allows parallel computing. From a reliability standpoint this is the best alternative since if one processor fails, the others can take over its work. The result is a graceful degradation of the system in which performance may be lost, but functionality is preserved. Among the disadvantages of this approach is that it requires a very complex software executive to transfer control and data. In fact, the management of resources may consume a significant fraction of the available computing. Of the three architectures, the distributed network of general purpose machines is the most promising but it still requires more research.

6.5.5 Reliability

The primary requirement of a spacecraft computer is that it be reliable and robust. It must avoid faults, it must continue to function in the presence of faults, and it must have a long operational life, especially for deep space missions. Faults arise from two sources. Physical faults are due to component failures, temporary malfunctions, or external interference. Man-made faults are the result of specification errors or bugs in design or implementation. Faults can also be categorized as hardware or software related.

Hardware reliability involves two classes of techniques, fault avoidance and fault tolerance, both of which are required in any reliable system. Fault avoidance, as the name implies, is aimed at minimizing the probability that a fault will occur. The methods used include utilizing reliable components and extensively testing them individually, using thoroughly refined techniques for the interconnection of components, packaging and shielding subsystems to screen out interference, and finally, extensive testing of the complete system. Unfortunately, fault avoidance is not a sufficient method for ensuring reliability since no fault avoidance techniques can totally prevent faults.

Fault tolerance assumes that faults will occur and is geared toward maintaining system operation even in the presence of faults. Fault tolerance involves fault detection for noticing when a fault has occurred, fault masking to isolate the errors to a single module, and fault recovery to correct the error. The basic technique of error recovery is to automatically switch out the failed component and switch in its place a duplicate copy. This is known as protective redundancy and is used at the component, subsystem, and entire system levels.

Software reliability is even less well understood than hardware reliability. It is an active area of research but represents a possible bottleneck in technology for future spacecraft computer systems. Current research includes structured programming approaches to program design, software engineering approaches to program development, verification and testing of programs, mathematical models for software reliability and prediction, and collection and analysis of software fault data.

Both hardware and software reliability are active areas of computer science research and much more still needs to be done.

6.5.6 Space Qualification of Computers

The final research area to be discussed under computing and control deals with space qualification of computers. Space qualification is the process of testing some system to be used in space against a demanding set of specifications including such aspects as temperature, radiation, vacuum, and vibration tolerance, and reliability. Computers that have been space qualified significantly lag the leading edge of earth-bound computer technology. The state of the art in space qualified computers is best described by the specifications for a fault tolerant space computer (FTSC) under development at the Raytheon Corporation [66]. The machine is to perform 250,000 simple operations per second, execute floating point and vector operations as well, and access up to 60K words of 32 bit memory. It will weigh 23 kilograms and consume 25 watts of power. Closing the gap between space qualified machines such as this and state of the art earth-based computers requires more research.

One approach to this problem is to develop a family of software compatible machines differing only in performance so that software can be written first and the latest advances in hardware can still be taken advantage of almost up to launch time. However, for very long missions, such as the Galileo Jupiter probe, new advanced software can be delivered to the spacecraft after launch, hence as much computation as possible should be done in software rather than be committed to hardware.

6.6 Communications

A communications system is essential to any space robot. This section discusses communication requirements, the state of the art in spacecraft communications, represented by microwave systems, and the research frontier of optical or laser communication. Much of this material is drawn from [69].

The communication needs of a space robot consist of communications with earth and with other spacecraft or robots. Communications with earth include the reception of high level commands from earth to the spacecraft and transmission of data from the spacecraft to earth, including still pictures and television. Spacecraft to spacecraft communication includes beacons or transponders for cooperative docking, and more general communication to enable cooperation in multi-robot tasks such as construction.

6.6.1 Microwave Systems

The current state of the art in space communications is represented by microwave systems using wavelengths between 1 and 10 centimeters. The primary advantage of microwaves over lower frequencies is that the high frequency and broad frequency spectrum allow high bandwidth communication. For example the ATS-VI communications satellite currently in space can handle 10^9 bits per second. Another advantage of microwaves is their high directivity which enables a narrow beam to be focused by a relatively small antenna. Similarly, microwaves can be transmitted by narrow waveguide tubes.

Microwave transmitters that have been space qualified include both linear beam tubes and solid state devices.

Linear beam tubes are the older, more established technology. Typical frequencies are 2 to 100 gigahertz with a bandwidth of .01 times the frequency. Gain is about 30 dB and modulation is by phase shift keying (PSK). RF power requirements are around 10 watts to reach the moon or Mars and about 50 watts for the outer solar system. Note that there is a tradeoff between power and frequency; lower frequencies require more power for the same range, and only low power, low frequency tubes have been space qualified. Up to 50% efficiency is achievable and lifetimes for linear beam tubes range from 10K to 100K hours, depending on power and frequency. A 10 watt transmitter weighs about 1 kilogram and takes up around 1700 cubic centimeters of space, while a 100 watt transmitter is twice as heavy and three times as large. In addition, the power supply is about the same size and weight as the transmitter.

For near-earth communication, solid state transmitters will become the dominant technology. A feasible data point is a 10 watt transmitter operating at 10 gigahertz with 40% efficiency, thus consuming 25 watts of power. Such a system would have a bandwidth of 50 megahertz, would weigh 2 kilograms, and would occupy 3400 cubic centimeters of space, including the power supply.

Microwave space receivers are based on solid state bipolar, or field effect, low noise amplifiers. Typical sizes and weights are 150 cubic centimeters and 1.8 kilograms. Power consumption is about 3 watts. Reliability is limited by the amplifier and is about 6.5 failures per million hours.

Large antennas are required for microwave satellite communication and observation from earth. However, high data rate, high gain directional antennas are used on spacecraft. Sizes range from .3 to 3 meters in diameter and a precision pointing and control system is necessary.

Effective bandwidth can be increased by various signal design and processing functions. For example, error correcting coding can raise the noise tolerance of a communications system. Modulation techniques such as single side band allow more information to be carried on the same frequency band. Finally, digital signal processing can be used to enhance transmitted data and effectively extract more information.

Large scale integration has produced combined microwave systems consisting of transmitter, receiver, antenna, signal processing, and control in a single communications package.

6.6.2 Optical Communications

The primary advantage of optical or laser communications is that the extremely high frequency of light offers almost unlimited bandwidth and breadth of frequency spectrum, virtually eliminating the problem of crowding. Another advantage is that since lasers generate coherent beams, relatively little power is lost in transmission. In addition, the short wavelength allows very thin waveguides or fiber optics.

The primary disadvantage of optical communications for space is that the lasers themselves are very inefficient. The two most efficient lasers are CO_2 and yttrium-aluminum-garnet (YAG). The CO_2 laser has a wavelength of 9 to 11 micrometers and is 15% efficient while the YAG laser has a wavelength of 1.064 micrometers and is only 2% efficient.

Another disadvantage is that due to the coherence of the beam, accurate beam steering is required for the transmitter, and the receiver must have a laser beacon for the transmitter to track. In addition, optical communications cannot penetrate weather.

Laser communication is currently a research problem even though a data rate of 10^9 bits per second (pulse modulated) has been demonstrated in the lab. A critical requirement is funding to space qualify laser systems. A feasible system that could become space qualified by the year 2000 includes a CO_2 laser with a range of 7.4×10^7 meters, a data rate of 10^9 bits per second, consuming a total of 250 watts of power, weighing 25 kilograms, and occupying .7 cubic meters of space.

6.7 Power Systems

A power supply is required for all of the subsystems of a space robot discussed so far, including manipulators, sensors, navigation, guidance, propulsion, locomotion, computing, and communication. There are basically three types of solutions to the power supply problem in space: the necessary power could be transmitted to the spacecraft, it could be collected by the craft, or the energy could be stored onboard. Each of these alternatives are discussed in turn. In addition, power conditioning and power system configurations are considered. Most of this material is from [22].

6.7.1 Power Transmission

The power required by a space robot could be beamed to the robot either from the ground or from an orbiting space station. Transmission could either be by microwaves or laser beams. Microwave power transmission is currently under development and is about 70% efficient. Laser power transmission is on the technology frontier and currently only has an efficiency of 30%. One of the advantages of laser beams over microwaves is that the laser requires smaller areas for transmission and collection. Microwave power transmission should become available for space by 1990 and laser systems by 1995.

6.7.2 Power Collection

The primary source of energy in space is solar radiation. This energy can be collected as thermal energy or directly converted to electricity by solar cells. Since thermal collection is impractical for small power systems, this discussion will focus on solar cells.

At a distance of 1 AU (Astronomical Unit or about 93 million miles) from the sun, the amount of energy in solar radiation is approximately 1.36 kilowatts per square meter. Due to solar spectral considerations, the theoretical maximum efficiency of solar cells is 22%. Current silicon solar cells are about 11% efficient. Furthermore, efficiency drops rapidly with increasing temperature. Solar cells are also subject to damage from high energy particles. Finally, note that solar cells are only useful at distances of up to 2 to 3 AU from the sun [52].

There are three different types of silicon solar cells available: conventional, lightweight, and low cost. Conventional solar cells are sufficient for power systems requiring less than 5 kilowatts, such as that of a space robot, and weigh 33 grams per watt of power at 1 AU. For power requirements between 5 and 100 kilowatts, lightweight cells weighing 15 grams per watt are more practical. For very large power systems over 100 kilowatts, low cost solar cells become attractive, but weigh 50 grams per watt.

6.7.3 Power Storage

Power storage devices include primary and secondary batteries, fuel cells, and radioisotope thermoelectric generators (RTGs).

Primary batteries are non-rechargeable and include lithium-hydrogen, alkaline-manganese, mercury, and silver-zinc. They produce about 140 watt-hours per kilogram. Secondary batteries are rechargeable but there are limits on the number of recharging cycles. In general, any rechargeable battery can be recharged 200 times, but mass and cost increase by a factor of two for 200 to 3000 charging cycles and a factor of four for 10K to 15K cycles. Candidate batteries include nickel-cadmium which can be recharged 15,000 times, silver-cadmium which allow 5000 charging cycles, silver-zinc which admit 250 cycles, and nickel-zinc batteries. Energy output is about 36 watt-hours per kilogram.

Fuel cells combine hydrogen and oxygen to generate energy and produce water as a byproduct. These devices have a lifetime of 5000-10,000 hours and generate 14 watts per kilogram. Some fuel cells are rechargeable by electrolysis.

A radioisotope thermoelectric generator (RTG) produces energy from the radioactive decay of a heavy isotope such as Cm^{244} or Pu^{238}. These generators produce 3.8 watts per kilogram, are available in .1 to 10 kilowatt units, and require minimal shielding. Note that in terms of Joules per kilogram, nuclear fuel is the most efficient way of storing large amounts of energy, by three orders of magnitude.

6.7.4 Power Conditioning

In addition to acquiring raw electrical energy, every power system must include a power conditioning subsystem to deliver the power to other systems in a usable form. Typical components of such a system include battery charger controllers, voltage regulators, rectifiers, and filters. Power conditioning systems are 60% to 80% efficient and weigh 20% to 40% of the weight of a solar panel of equivalent power output [52].

6.7.5 Power System Configurations

Typical configurations for a spacecraft power system depend on the duration of the mission. Missions lasting less than two weeks can satisfy their power needs with just fuel cells and batteries. Missions exceeding several weeks require solar cells plus a battery or RTG. Deep space probes to Jupiter and beyond must rely on RTGs for their electrical power.

6.8 Spacecraft Structure

The final system to be considered for a space robot is the actual spacecraft structure itself. The spacecraft must protect all the other systems from harsh features of the space environment and hazards of space flight. In addition, an environment control system is required for the interior of the craft. Much of this material is drawn from [5].

The primary requirement of a spacecraft is light weight, hence the principle materials used in construction are aluminum and magnesium alloys. The rest of this section discusses some of the subtler aspects of spacecraft structure.

6.8.1 Features of the Space Environment

Features of the space environment which must be taken into account in the design of a spacecraft include radiation, temperature extremes, zero gravity, vacuum, and micrometeoroids.

The sources of radiation in space include solar radiation trapped by the earth's magnetic field (Van Allen belts), solar wind and flares, galactic cosmic rays, interactions of radiation with spacecraft materials, and onboard nuclear power systems. Note that radiation is more intense at higher orbits such as geosynchronous orbit. The primary impact of radiation on spacecraft is that electronics become sensitive to radiation at 10^5 rads [45]. In addition, radiation pressure can affect large, flexible members such as antennas. In order to provide radiation shielding, many spacecraft are coated with silvered quartz, which acts as a mirror. However, this material is heavy and expensive.

Temperature extremes are another feature of the environment which must be dealt with. The main source of the temperature problem in space is that the lack of an atmosphere results in a large differential between sun and shade temperatures. An additional concern is the impact that the vacuum has on heat dissipation. Since there is no atmosphere to conduct or convect heat way from the spacecraft, all heat dissipation must be by radiation [55]. Finally, the heat of reentry creates an even more severe problem. The impact of temperature extremes on a spacecraft manifests itself in several ways. Increased temperature markedly decreases the efficiency of solar cells. Heat also adversely affects the reliability of electronics. In the future, any superconducting electronic systems will require very low temperatures to operate.

The solution to the temperature problem consists of passive and active controls. Passive controls include insulating and reflecting shields, which are heavy and expensive. Active controls consist of heating and cooling, which consume excessive amounts of power.

The most ubiquitous feature of the space environment, zero gravity, actually works to the advantage of

spacecraft designers since it results in low structural loads. On the other hand, all mechanical systems must work in zero-g.

The hard vacuum of space poses some problems for the spacecraft designer. In addition to the temperature problems due to the lack of an atmosphere, the vacuum has a slight effect on pressure vessels, which are primarily used for fuel. Solid fuels require high pressures in the range of 500 to 1000 psi. Liquid fuels require only low pressure containers of 10 to 100 psi.

Finally, micrometeoroids must be considered. Micrometeoroid particles can strike a spacecraft at up to 225,000 feet per second. Unfortunately, protection from these particles is still an empirical science and more research is needed in this area.

6.8.2 Hazards of Space Flight

In addition to features of the space environment, there are several aspects of space flight that must be taken into account in the design of spacecraft structures. Propulsion loads include shock, acceleration, deceleration, vibration, and torsion. The attitude control system imposes loads which require a certain level of structural stiffness in the craft. Inertial loads and balancing must be considered. Atmospheric loads include drag in low orbits and pressure variations due to aerodynamic reentry loads. Finally, possible sloshing of liquid fuels must be anticipated.

Given the above technology assessment and identification of outstanding research problems, we now turn our attention to a research program designed to address those problems.

7. Research Program

7.1 Introduction and Overview

This chapter sketches a research program designed to achieve the goal of an autonomous space robot. It presents a series of incremental research goals embodied as space missions.

The goals of the program are to develop autonomous space robots. Examples include a deep space orbiting probe, a lunar or planetary roving surface vehicle, and a general purpose earth orbiting space robot. The degree of autonomy expected in such missions is the ability to execute very high level goals from mission control without further communication from humans or ground computers. Examples of such goals would be to explore a particular area of a planet, repair a particular satellite, or recover a particular object in space.

There are several constraints that such a research program must satisfy. First and foremost is that it must achieve the above goals. In addition, the missions in the program must form a developmental sequence in the sense that each new mission should require only an incremental advance over what has already been accomplished. In order to receive continued funding, each of the missions in the program must independently serve a useful function. Note that there may be more efficient or cost effective ways of achieving these intermediate goals, but that is the price that must be paid for the long term goal of autonomous robots. The final constraint is a pragmatic rule that as far as possible any technology that is to be incorporated in a space mission should be demonstrated on earth first. For example, serious efforts to develop autonomous planetary rovers should await the construction of autonomous roving vehicles on earth.

The proposed research program consists of a sequence of four separate missions. First is a smart sensing spacecraft containing an array of sensors plus a powerful computer system for data analysis, reduction, and sensor control. The primary research goal of such a mission is to close the technology gap between current earth computers and space qualified computer systems.

The second stage is a general purpose, free flying space robot for earth orbit. Such a vehicle would be capable of autonomous locomotion and manipulation. Typical applications include satellite deployment, retrieval, and servicing.

The third step is a lunar or planetary surface rover. Such a vehicle would be essential for cost effective exploration of the solar system. This mission could be pursued in parallel with the free flyer but does depend on the computer technology developed in the first mission.

The final stage of the research program is the development of robots for space construction. The fundamental research problem of this step is how to organize a large number of cooperating robots to accomplish a single task.

For each mission, the boundary between supervisory control and autonomous operation should be flexible. Supervisory control refers to a control strategy that lies between pure teleoperation and pure autonomy in which one supervisor manages one or several robots by issuing intermediate level commands. The supervisor may be either a human operator or a ground based computer. One of the reasons for allowing supervisory

control of these missions is that presumably more complex tasks could be handled with supervisory control than with autonomous control and hence the utility of the individual missions would be enhanced. Another advantage is that in the event that artificial intelligence does not advance as fast as anticipated, the capability for supervisory control provides a contingency plan for recovering some benefits from a mission. However, this aspect could work to the disadvantage of the goal of autonomous operation in the following fashion: In the face of technological problems or budgetary restrictions, there will be strong pressure to sacrifice autonomous operation, since such a move may not jeopardize the interim goals. This pressure must be resisted in order to achieve the log term goal of autonomous space robotics.

7.2 Smart Sensing Spacecraft

The first step in the proposed research program is to design, construct, and successfully test a spacecraft with a collection of sophisticated scientific data sensors, and a powerful onboard computer system. The computer is used to control the sensors by deciding what data to acquire, analyzing the data to decide what to record, and reducing the data to make optimal use of the communications link with earth. The contribution of such a mission to the overall goal of autonomous robots is to narrow the gap between ground based computer technology and space qualified computer systems.

7.2.1 Rationale for Smart Sensing

There are several reasons for incorporating significant processing power onboard a sensing spacecraft. One of the most compelling is that new sensors for earth resources satellites have data acquisition rates that surpass the rate that information can be transmitted to earth. The effective bandwidth to earth is determined by the actual bandwidth of the communication link and the capacity of the craft to buffer information when it is not within the range of a receiving station on earth. Since the total quantity of data available to the spacecraft cannot be relayed to earth, some decision making and data reduction capability must be included onboard to filter the data.

Another reason for onboard processing is for making decisions in response to sensory input in deep space. For example a solar observatory in a polar orbit around the sun with the goal of observing and recording solar flare activity would have to decide onboard when such an event was occurring since the communication delay to earth is long in comparison to the duration of such events. Similarly, a Venus orbiter designed to look through occasional and temporary holes in the clouds would have to recognize such opportunities immediately. As another example, a probe to the outer planets designed to release multiple hard-landing surface probes could be programmed to recognize potential landing sites and drop a probe on such sites. This is particularly important if the orbiter is surveying the entire planet and will not return to the same point in its orbit.

Current satellites can be fitted with sensors which have some flexibility in what data they acquire, such as instruments that can be pointed in different directions or can be tuned to receive information from different parts of the electromagnetic spectrum. Obviously such satellites must make choices about what to "look" at. One mechanism to accomplish this would be to scan the entire spatial or frequency range available to the sensor at low resolution, evaluating images with respect to preprogrammed "interestingness" criteria, and focusing at high resolution on interesting areas.

The detection and recognition of transient or rare phenomena requires sophisticated onboard processing power in a satellite. Examples include forest fire or tornado detection over land, and finding ocean storms or icebergs over water. An important military application would be a satellite to augment the Defense Early Warning system (DEW line) for detecting hostile aircraft or missiles aimed at the U.S.

A final reason for including powerful computing onboard a satellite is the economic notion of complexity inversion. Consider a satellite based personal communication or electronic mail system. By putting the complexity of such a system into space, the corresponding ground elements, of which there are many, can be small, simple and inexpensive. Another example of such a system is a satellite global navigation system with collision and hazard warning.

7.2.2 Computing System Architecture

The simplest computer architecture that will support the applications mentioned above is that of a medium scale general purpose central computer. The level of computing power required is approximately a 1 MIP (million instructions per second) central processing unit with a megabyte of primary semiconductor memory. The central computer would control data collection, reduction, storage between dump intervals, and transmission to earth. In addition, it would provide control of flexible sensors. Software for different applications would be downloaded from earth. Such a spacecraft could be time-shared between different tasks by periodically swapping the software. In addition to the central computer, the spacecraft may have several dedicated microprocessors for data reduction signal processing functions and real time control of tracking or scanning sensors.

7.2.3 Research Issues

All of the applications mentioned above can be accomplished with current hardware and software systems on earth. The primary research problem in this stage of the program is how to close the technology gap between ground based and space qualified computing systems. It is estimated that spacecraft computing is ten to fifteen years behind the current state of the art. One of the reasons for this is the constraints imposed by space qualification on size, weight, power consumption, and temperature, radiation, and vibration tolerance. However, the most important obstacle is reliability, both hardware and software.

7.3 Free Flying General Purpose Space Robot

The second stage of the proposed research program is a general purpose free flying space robot. Given that the first stage has brought space qualified computing systems up to the level of ground based technology, the additional problems to be addressed in this stage are autonomous onboard navigation, guidance, and propulsion, and sensor referenced control of manipulator systems.

7.3.1 Applications

There are numerous applications for a free flying space robot in earth orbit. For example, the deployment of satellites from the shuttle cargo hold and the retrieval of satellites for return to earth can be more efficiently accomplished with a small robot than with the shuttle directly. Such a robot could also service faulty satellites

at least at the level of removing and replacing failing boards. The collection of certain types of space garbage may become desirable at some point, a job well suited to a general purpose free flying robot. Finally, the rescue of an astronaut from space could be accomplished with a robot.

7.3.2 Functional Requirements and Research Issues

With the above applications in mind, we can enumerate the required capabilities and the outstanding research problems posed by such a robot.

The first problem is detecting and locating a target object. Radar is likely to be more useful than vision in this task due to the sparseness of the space environment.

Once detected the target object must be tracked to determine its precise orbit. Similarly, the current orbit of the robot must be known. This information would be available from an onboard inertial navigation system.

Given the navigation parameters of both the target and the robot, a trajectory for intercepting the target with the robot must be planned. Note that the problem is one of orbital transfer rather than simple straight line motion. This step involves tradeoffs between time, energy, and propellent mass. The amount of energy and propellent expended is directly related to the speed with which the rendezvous occurs. In addition, for a given maneuver, the amount of energy required is inversely related to the quantity of propellent mass expelled. Trajectory planning is normally accomplished by obtaining an analytic solution to the two body problem of the robot and the earth as an initial approximation, and then refining it numerically to take into account variations in the earth's gravity and the effect of other bodies such as the moon and sun.

The planned trajectory must then be executed with chemical rockets for propulsion and gyroscopes for attitude control. The inertial navigation system must be used in a feedback loop for course corrections. Similarly, as the robot approaches the target, a laser or radar ranging system will be required for final adjustments relative to the target. Note that the number of course corrections can be traded off against accuracy in the initial trajectory planning.

The above problems of tracking and intercepting a satellite are currently solved on large, main frame computers on the ground. The research issue here is to be able to solve these problems with the spacecraft's smaller onboard computer.

Once the relative translational motion of the robot and the target object has been cancelled out, the target may still be spinning and tumbling in an arbitrary fashion. Note that for a body with no unbalanced forces on it, the rotational components around the x, y, and z axes can be resolved into a constant rotation about a single resultant axis. This implies that each point on the object is moving in a simple circle. Given a vision system with a source of active illumination, a single feature point can be detected and tracked to determine the axis and speed of rotation of the target. Note that the feature point must be tracked through 180 degrees of lighting angle and must be reacquired when it returns to view from the far side of the object.

After determining the precise rotational motion of a target object, the relative rotational motion of the robot and the target must be cancelled out. One approach would be to slow the target by carefully applying friction to it with an arm of the robot. Alternatively, the robot could use its thrusters to orbit the target at an angular velocity that matches the rotation of the target.

The next step is contact or docking with the object. For the satellite deployment, retrieval, and servicing applications, docking can be accomplished with a specialized and standardized docking arm on the robot that matches a corresponding receptacle on the satellite. Such a standard system has been worked out for the shuttle manipulator arm and satellites to be carried on the shuttle. However, in the case of garbage collection or rescue, the robot must have a much more general gripper for docking and must find a suitable "handle" on the target object.

After the robot and target object are linked the resulting system composed of the two bodies must be passivated or despun and must be propelled to a destination such as the shuttle. In the case of a friendly satellite, the mass and moments of inertia of the object would be known and hence the mechanics of the two body system could be predicted. However, in the case of a more general object, the mass and moments of the combined system must be determined experimentally by executing test burns and analyzing the resulting accelerations sensed by the inertial navigation system.

Servicing of a satellite in orbit requires some manipulation capabilities in addition to the above functions. A scenario might proceed as follows: After docking with the satellite, the robot connects a plug to a special diagnostic receptacle on the satellite and runs diagnostic software to determine the faulty module. Next a protective cover over the electronics bay is removed, the suspect module is removed and replaced from spares carried by the robot, and the cover is replaced. After rerunning the diagnostics to verify the repair, the plug is removed and the robot undocks. Note that such a repair scenario depends upon designing satellites for repair in the first place.

Presumably by this stage in the research program, the level of manipulative capabilities indicated above will have been accomplished on earth. Note that manipulation tasks are subject to a tradeoff between speed and power consumption of the manipulator. However, one difference between manipulation in space and on the ground as that the lack of gravity allows manipulation with arbitrarily low forces if time is not critical. For example the shuttle manipulator arm cannot even lift its own weight in earth's gravity.

The final problem to be addressed is undocking of the robot and target body. The critical requirement here is that the robot not impart any momentum, either linear or angular, to the object in the undocking process.

7.4 Lunar or Planetary Surface Rover

The next step in the research program is the development of an autonomous roving surface vehicle for exploration of the Moon, Mars, or other planets. This stage can be worked on in parallel with the free flying robot since it does not depend on the solution to problems addressed by that mission. However, it does depend on the computing technology to be developed for the smart sensing spacecraft.

A detailed application scenario for such a rover was presented in section . The primary research problems are path selection and planning, addressed in section , and mobility and locomotion (see section).

This technology should not be developed for space before it can be convincingly demonstrated on the earth on terrain that resembles that encountered on the Moon or other planets. Areas such as the Craters of the Moon National Monument in Idaho, with 74 sq. mi. of lava flows and other volcanic formations provide suitable environments for the testing of such vehicles.

The problems addressed by a space rover are nearly identical to those encountered on the earth. While the Moon presents a low gravity environment that would significantly impact the design of a rover, other bodies such as Mars have gravity very close to that of Earth. Similarly, while the lack of atmosphere on the Moon creates special problems associated with temperature control, radiation, and difficult lighting, bodies such as Venus have atmospheres much denser than Earth's. Thus, in general, the problems of lunar or planetary rovers are not significantly different than those for an earth vehicle.

However, development of a space rover is included as a major part of this research program for two primary reasons. One is that such a vehicle is essential in order to explore a significant portion of any body in the solar system in a cost effective manner. Stationary surface probes cannot adequately cover an area of a planet and orbiting probes cannot examine samples of surface material. The second reason is that a surface rover requires significant autonomy and can only be efficiently operated in a very high level supervisory mode due to communication time delay to a planet and communication blackouts on the far side of the moon. Thus, such a mission will necessarily drive artificial intelligence research for space and be less susceptible to pressures to increase the level of ground based control.

7.5 Space Construction Robots

The final stage in the proposed research program is the development of robots for use in space construction. A prerequisite to this stage is the successful demonstration of the general purpose free flying robot proposed in the second stage of the program. The fundamental additional research problem to be addressed at this step is how to organize a large number of robots to accomplish a common task. Note that the development of a surface rover is not a prerequisite to this stage.

An example of a space construction task for which robots would be required is a solar power satellite. This structure shares two common features with many proposed space construction tasks: it is very large, and has a very regular structure. The size of a practical solar power satellite, on the order of 5 kilometers by 10 kilometers, implies that many space robots will be required to construct it in a reasonable amount of time.

. The regularity of space construction suggests that a fair degree of specialization of the construction robots will contribute to efficiency and economy in the task. For example, most robot systems are subject to a tradeoff between size and power on the one hand and dexterity on the other. Hence, we can expect that large, powerful, but clumsy robots will be used for moving beams and materials and smaller, less powerful, but more dextrous robots will be used for connecting components.

As mentioned above, the fundamental research problem to be addressed at this stage is how to control multiple, cooperating robots to accomplish a common goal. This is analogous to the distributed processing problem for computing systems except that the goals involve real world sensing and manipulation rather than strictly information processing.

The simplest approach to the problem is that of one central computer controlling all the robot slaves in a supervisory manner. The difficulty with this organization is that the computing speed, memory capacity, and communication bandwidth of the central computer will limit the number of robots that it can control, even in supervisory mode.

An alternative is a completely distributed control scheme where each robot has an equal share in the management of the task. The obvious problem with this approach is that there are no effective mechanisms for creating, communicating, and changing high level goals in the task.

Perhaps the most effective organization for space construction is a hierarchical one. This implies the existence of "robots" at the middle levels of the hierarchy which have sensors, a large concentration of computing power and communication capacity, but no manipulation capabilities. These robot managers have supervisory control over a number of robot workers and in turn are controlled by higher level managers.

The above organization is almost identical to most large human organizations on earth and one might ask why the same type of structure would be the best choice for space construction. The reason is that hierarchical organization is a very general mechanism for managing complexity and is based on the near-decomposability of the task, the locality of information necessary to accomplish subtasks, and the variation in the degree of coordination required among subgroups working on the task [68].

One of the important features of a hierarchy is the branching factor. For a given number of robot workers, the branching factor will determine the number of managers required and the depth of the hierarchy. The branching factor is determined by the number of robots that a single manager can effectively control. Note that by increasing the intelligence of the workers, less control is required of the manager and hence the manager can control more workers. For human organizations, the branching factor is about five. Experience with existing hierarchical computing systems indicates that for a robot construction team the branching factor will be higher, on the order of ten to fifty.

7.6 Summary

The research program outlined above is geared toward development of completely autonomous space robots, and consists of four stages. The first is a smart sensing spacecraft with the research goal of closing the technological gap between ground based and space qualified computing systems. The second is a general purpose free flying robot addressing the problems of onboard control of navigation, guidance, propulsion, and manipulation. The next stage is the development of autonomous surface rovers for lunar or planetary exploration. The final step is aimed at robots for space construction and deals with the issue of the distributed processing problem in robotics. The first, third, and final stages form a strict developmental sequence, while the surface rover depends only on the first stage and is not a prerequisite to the later stages.

8. Anthropomorphism Considered Harmful

The execution of any research program is subject to the prevailing paradigm of the science. In robotics, the most common research paradigm is to imitate the functions and structures of humans. This section discusses this tendency toward anthropomorphism in robotics and cautions against this approach in the development of space robots.

Throughout the history of technology, the development of a new machine has often begun with an attempt to imitate nature. Flying machines patterned directly after birds are a prime example. However, these attempts have usually been shortlived and the successful development of the machine has often been the result of a radically different mechanism. Thus in most cases where similar functions are performed both by naturally evolved species and by man-made artifacts, we find that the machines usually employ different methods than nature does. Birds flap their wings for propulsion whereas airplanes spin propellers or use jets; animals move on land with legs while vehicles use wheels and axles; animals communicate with acoustic signals whereas most man-made communication systems employ wires or electromagnetic waves. This phenomenon even extends to mental tasks: humans play chess by using a tremendous amount of knowledge and relatively little search, while computers play chess with a great deal of search and a comparatively small knowledge base.

The fundamental reason for this disparity is the tradeoff between power and generality that we find in almost all classes of systems. High performance in any particular task only comes at the cost of competence in a number of tasks and vice versa. Evolution of natural species favors adaptability over specificity. However, in building machines, we tend to optimize them for the intended task and sacrifice related tasks. Natural systems are found near the general end of the spectrum whereas artificial systems exist near the powerful end. For example, legged locomotion is extremely general, being effective in almost all terrain, including mountains and trees. However, on smooth hard surfaces, wheeled vehicles can cover larger distances at higher speeds with less energy consumption (a man on a bicycle is the most efficient animal powered travelling machine). We even amplify the performance of our machines by tailoring their environment to suit them, for example by building roads and railroad tracks.

Robotics, as a new science dealing with machines that manipulate objects, manifests a great deal of anthropomorphism. In light of the above considerations, we should expect that a single minded pursuit of the anthropomorphic approach to developing robots would ultimately limit their performance. For example, many researchers view the human arm and hand as the ultimate manipulator system. However, for almost all applications a continuous roll wrist is superior to the human wrist. As another example, most robot arms have special purpose tools such as arc welders or spray painters attached to their ends as opposed to general purpose grippers.

Another reason for the anthropomorphism of current robots is that the technology is being driven by industrial automation. Since factories were designed for human workers, in order for robots to replace the humans they must initially perform similar tasks in a similar environment, and this results in robots that are similar to people. As robot factory workers gradually outnumber their human counterparts, we can expect the factories to be redesigned to suit the robots, and redesign of industrial robots to suit the new factories to occur simultaneously. However, in space, we have no such initial conditions or compatibility problems to retard development of the ideal robot. We have the opportunity to create an entirely new technology, such as space

construction, tailored to the requirements and capabilities of mechanical as opposed to human workers. For example, there may be a method for simultaneously joining three or more beams but which does not allow a stable connection to be made between only two beams. Such a technique would be very difficult for a human to perform but may be easy for a three or more armed robot.

Another way of viewing this is that humans are a product of the environment they evolved in and hence we should expect robots that are suited to operating in this same environment to be of similar form. On the other hand, the environment of space is radically different from that of earth and it would be surprising indeed if a well adapted inhabitant of space was not radically different from what we find on earth.

This issue is also an argument against the pure telepresence approach to space operations. By directly projecting our human capabilities into space, we are bound to design our space technologies to suit human, albeit remote, workers.

The point is that in designing space robots, we must try to give our imagination free rein to meet task requirements without being constrained by models that exist in nature. Admittedly this is a difficult problem. Examples of such thinking include arms with infinite articulation, such as Minsky's fourier arm concept [55], and Moravec's idea of robots with virtually an infinite number of appendages [58].

9. Economics and Politics of Space

Any research proposal for the future directions of a technology would be incomplete without a discussion of factors outside the scientific domain. Not surprisingly, the future of space does not hinge solely on a set of scientific and technological questions. Political and economic considerations are equally important in determining the directions that our space program will take. Criswell [14] has studied the rationales and key technologies of space industrialization with a view toward economic and political issues.

The origin of the space program was a political decision to compete with the Soviet Union in an extension of the cold war fought above the earth's atmosphere. Wolfe [76] points out that President Kennedy hitched his political fortunes to Project Mercury and the "New Frontier." The goal of putting a man on the moon was established and tremendous resources were allocated with relatively little dissent. In 1965, NASA was the fourth largest industrial economic entity in the U.S. in terms of cash flow [14]. The total cost of Project Apollo was about $40 billion.

After the lunar landing goal was reached in 1969, the posture of Congress and the nation toward space changed from an attitude of what can we accomplish in space to an attitude of what is the best way to allocate our scarce national resources in view of pressing problems on earth. NASA went from being the 4th largest "company" to 48th largest in 1976 [14]. The space shuttle program to date has cost only $10 billion [67]. Indeed, many of the delays in the shuttle program are blamed on the fact that budget constraints only allowed the investigation of one solution at a time for a technological problem, as opposed to the multi-pronged attacks that were common in the Apollo project [63].

Looking to the future, projects such as a solar power satellite would require on the order of $100 billion to develop [43]. Clearly, NASA could not support such ventures in its current budgetary position. Funding for significant future space applications must come from outside sources. Funding for space exploration missions can be expected to come from traditional governmental sources of scientific support, such as the National Science Foundation, the Department of Defense, and the Department of Energy. However, much of the support for global information services and space industrialization must come from the private sector via the profit motive. Examples of commercial space operations include those of companies such as COMSAT and the satellite business communications services currently being marketed by Xerox, IBM, and AT&T [65].

The role of NASA in such a future would be twofold. First, NASA must undertake a clear theoretical investigation of space industrialization. Second, NASA must develop and demonstrate the feasibility of key material gathering and processing functions in space. This will be followed by development of the economically viable industrial operations by private industry. This model of government funding of research in a new technology followed by private development has been followed in the aircraft, nuclear reactor, and computer industries.

After a sufficient commercial return from space has been realized, the private sector can be expected to take over the research and development of new applications. Von Puttkamer [63] estimates that the revenues from space will reach $2 billion per year in 1990 and $80 billion per year by 2010, with half of that in communications alone. Space industrialization should become self-sufficient by 1995.

An alternative scenario for the future of space is that space technology will be driven and funded by

military applications, such as reconnaissance and weapons in space. There currently exists a large scale military space program entirely separate from NASA. The defense department has booked a large percentage of the scheduled shuttle flights and is building its own launch and landing facilities for the shuttle at Vandenberg Air Force Base. In addition, the Air Force plans to build a $450 million space operations center at Peterson Air Force Base in Colorado to direct military shuttle and satellite operations and is requesting $150 million for anti-satellite weapons research [67]. The military applications of space are largely ignored in this paper due to the classified nature of the information.

10. Conclusions

Many future space applications will require intelligent action and manipulation in space. These include deep space probes, lunar or Mars rovers, satellite maintenance and repair, space construction, and space rescue missions. Remotely controlled teleoperators suffer from transmission time delays, limits on information flow, high personnel costs on the ground, and operator performance limits. Autonomous space robots are a feasible alternative to teleoperators. The requirements of a space robot can be met by the current state of the art in navigation, guidance, propulsion, communications, electrical power, and spacecraft structures. More research is still needed in manipulators, sensors, rover mobility, locomotion, and path planning, and computing and control. This research could be accomplished in a four stage program including a smart sensing spacecraft, a general purpose free flying robot, a lunar or planetary rover, and robots for space construction. The execution of this program should strive to reach beyond the anthropomorphic paradigm of robotics, especially in an environment such as space. The stimulus to carry out this program must come from the government and ultimately the decision will be based on political and economic considerations as well as scientific issues.

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